The Flight of Birds

JOHN H. STORER

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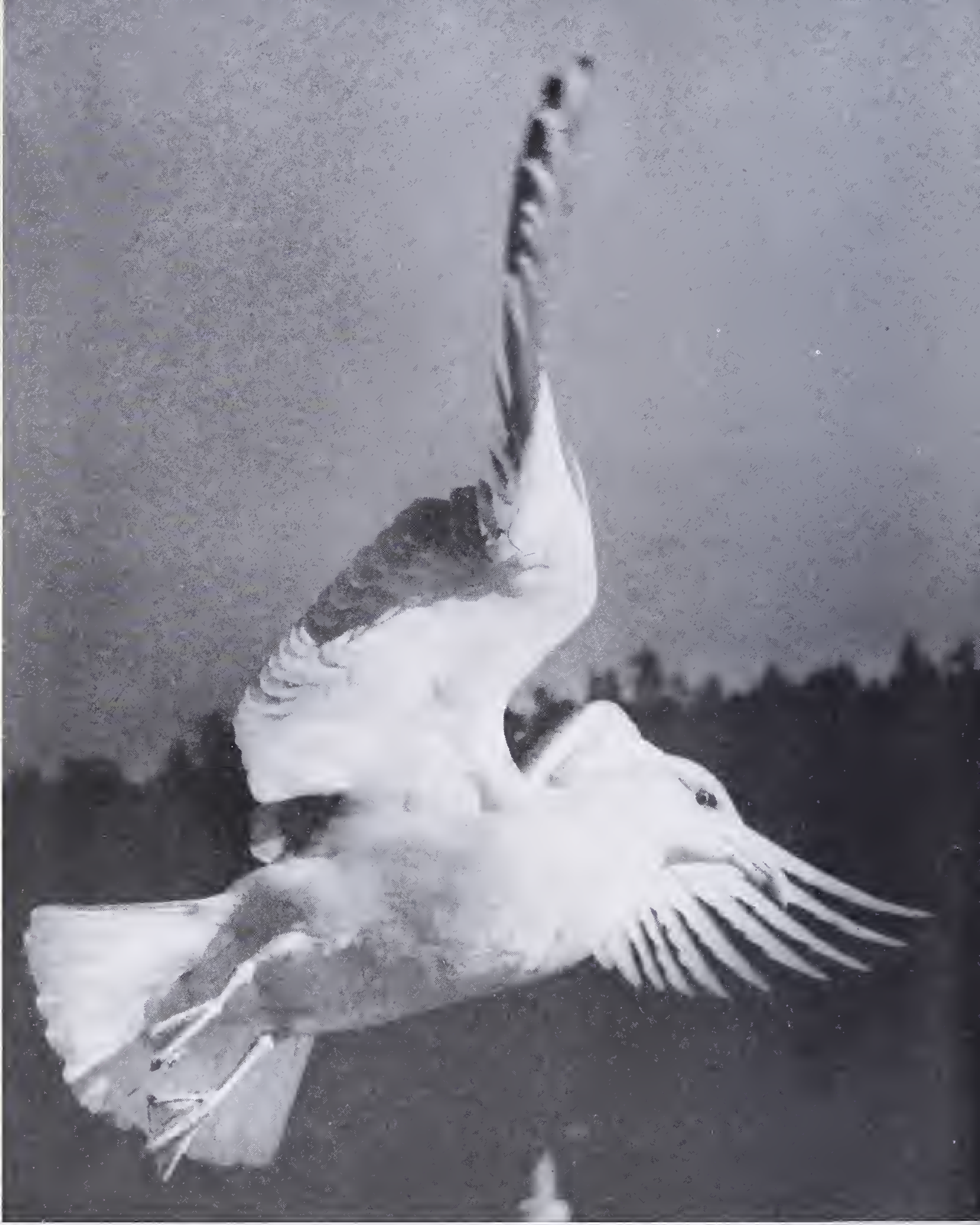
THE FLIGHT OF BIRDS



A flying gull, its wings in back stroke, demonstrates the lifting function of the inner part of the wing, the propelling role of the outer portion.—Courtesy Ansco.

The Flight of Birds

analyzed through slow-motion photography

by JOHN H. STORER

CRANBROOK INSTITUTE OF SCIENCE
Bulletin No. 28

598.2
St74

Copyright December, 1948
Cranbrook Institute of Science
Bloomfield Hills, Michigan

Printed by the Cranbrook Press, *Bloomfield Hills, Michigan*

Dedicated to my dear wife
who shared so largely in the happy experience
of this inquiry into the miracle of bird flight.

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Foreword

There is an apocryphal story that an airplane engineer, persuaded to investigate the mechanics of bird flight, announced after concluding his studies that he was prepared to prove mathematically that birds could not fly! While the mysteries of bird flight cannot yet be wholly explained, we now know something about the fundamental principles involved. Moreover, human interest turns naturally to a comparison between the man-made airplane and the most perfectly evolved living flying machine, the bird.

Mr. Storer became interested in bird flight as a result of many years of successful experience in taking colored motion pictures of various types of birds in flight. Free use of a slow motion camera produced hundreds of "shots" that revealed birds' wings in positions that would appear astounding and even incredible to the average person, since human vision is quite unable to perceive them. Convinced that every position had a definite purpose and a scientific explanation, Mr. Storer undertook to find out as much about bird flight as he could. The present book is the product of his studies. It attempts to explain as simply as possible to readers, who will be neither mathematicians nor physicists, how heavier-than-air machines fly through the air and why it is possible for them to do so, and to describe those structures of the bird's wing which are analogues of various parts of the airplane wing.

Much of the "mystery" of bird flight in earlier times was due to lack of knowledge of the properties of air and of what happened when a solid body moved through it at various speeds and angles. This is the modern science of aerodynamics, the elements of which are explained in one of Mr. Storer's opening chapters. Here the illustrations, consisting of reproductions of air flows caused by solid bodies placed in wind tunnels, are helpful and interesting. This section leads, naturally, to a discussion of the principles of constructing an airplane wing in such a way that maximum lift and minimum drag are obtained. Other technical details or structures, such as "slotting" and the "flap," are clearly explained and illustrated.

Bird flight can be classified as of these principal types: (1) propulsion by means of steady and regular flapping or beating of the wings, (2) non-flapping flight, including gliding, soaring, and sailing. The airplane most nearly corresponds to the flapping bird, but the bird's wing has a double function. Not only does it serve the same function as the airplane wing, but the flaps or beats also provide the force for propulsion, which in the airplane is supplied by the engine and propellers. Mr. Storer shows that certain parts of the wing produce the necessary slotting and perform the same function as the airplane flap.

To the human eye the beating of a bird's wings in flight looks like rowing. Centuries ago Leonardo da Vinci wrote a pamphlet on bird flight, which he attempted to explain in two ways. The wing beat down to lift the bird up, and the wing tip described an alleged line from the front to the rear to drive the bird forward. He was entirely wrong. Slow motion pictures show that a bird's wing rotates and tilts in flight and that propulsion comes from the outer half of the wing tip, the feathers of which may be bent almost at right angles. These pictures show other things as well. But let Mr. Storer tell his own story.

The principles of non-flapping flight were first suggested, I believe, in 1883 by Lord Rayleigh, who remarked that whenever a bird pursues its course for some time without working its wings, one of three things must be true: (1) the course is not horizontal, (2) the wind is not horizontal, or (3) the wind is not uniform. This generalization has proved to be sound in the main. Actually, soaring and gliding are more readily explainable to a layman than flapping flight. In his discussion of the subject Mr. Storer is broad-minded enough to point out that we still have much to learn. The albatross, with its long pointed wing, is the world's most perfect glider. Why, then, do land soaring birds have a slotted wing tip, theoretically less efficient?

The ornithologist is open to suspicion of prejudice in concluding that birds are still immeasurably more efficient as fliers than are the machines invented by man. However, there is ample justification for supposing that helicopters, autogiros, and gliders will be perfected to a degree which will make it possible to use them for practical purposes. There remain the art of navigation and the added difficulties and dangers of travel by night and in heavy fog. These conditions have been routine experience for unnumbered millions of birds for uncountable milleniums. Birds need no instruments, nor are they dependent upon trained pilots. While, therefore, mystery and much wonder remain for those with minds open to the marvels of the natural world, this mystery itself will stimulate the reader to reflect on Mr. Storer's excellent book. He will not have read it in vain. His store of information will have been enriched and some elements of his curiosity satisfied.

LUDLOW GRISCOM
Museum of Comparative Zoology
Harvard University

Acknowledgements

THE LINES OF inquiry followed during this study of bird flight led in many directions. In their pursuit I received invaluable help and suggestions from many people. I should like to express my appreciation to the following: Mr. John H. Baker and the National Audubon Society, whose cooperation helped so greatly in taking many of these pictures. Mr. Devin Garrity and Mr. Richard H. Pough, who first suggested that the pictures might supply worthwhile material for such a book. Dr. Alexander Wetmore, for encouragement to believe that this study might make a contribution in the field of ornithology. Dr. Robert Cushman Murphy, whose suggestions led to invaluable help in furthering the inquiry. The American Philosophical Society, for a research grant for a study of the soaring of the California Condor. Professor Richard H. Smith, of the Massachusetts Institute of Technology, for his very helpful suggestions toward the study of aerodynamics and for his help in the analysis of wing actions. Mr. Ben Shupack, President of the Soaring Society of America, and Dr. August Raspet, for their great assistance in analysis of wing motions and for constructive criticism of the text, especially in the chapter on soaring and gliding. Dr. R. D. Montgomery, research engineer, and Professor Arnold M. Kuethe, of the University of Michigan, for reading and criticizing the section on aerodynamics. Mr. G. W. Lewis, of the National Advisory Committee for Aeronautics, for help and suggestions in the analysis of wing action and design.

My own photographs have been supplemented by drawings and photographs by others to whom grateful acknowledgment is given. I am indebted to Mr. Francis Lee Jaques for his beautiful line drawings (Figs. 18, 26–29, 95, 96, 104, 106, 108, 110, 116) of feathers and wing action; to Mr. W. A. Jeffery for his fine diagrams (Figs. 2, 10, 20, 70) in the section on aerodynamics; to Mr. William Tarkington for his diagram of an aeroplane (Fig. 69), and to Miss Judy Hudgings for her help in this section. Thanks are due for the use of their photographs to Dr. Harold E. Edgerton (Figs. 59, 60); Mr. J. R. Pemberton (Figs. 139, 149–155); Mr. Hugo Schroder (Figs. 73, 156, and the dust jacket); Ansco (Frontispiece); Miss Luella Schroeder (Figs. 32, 37, 145); and the National Advisory Committee for Aeronautics (Figs. 1, 3, 4, 8, 9, 11, 12). Permission to use illustrations from their publications is acknowledged gratefully to the Scientific Monthly (Figs. 136, 137) and John Wiley and Sons, Inc. (Figs. 5, 6,). The publishers of Audubon Magazine generously permitted use of cuts, their property (Figs. 135, 138).

Most particularly I wish to express my gratitude to Miss Dorothy Tyler for her help in preparing my manuscript for the publishers, and to Dr. Josselyn Van Tyne, of the University of Michigan, for a critical review of the whole manuscript and proof. Last, but not least, I acknowledge a debt to Dr. George Miksch Sutton, whose advice led me to Cranbrook Institute of Science and its Director, Dr. Robert T. Hatt, who has worked on every stage of this volume, its editing, design, production and distribution.

J. H. S.

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1. Introduction

THE HUMAN senses were not designed for an accurate study of motion. Color and sound, coming to us as waves of vibration, are picked up by eyes and ears and translated into form and color and music. But many of these waves are outside the range of our senses —too fast or too slow to register. They do not exist for us unless they are caught on a photographic plate and converted into a form that we can see.

So it is with the beautiful and interesting forms that move around us. We are conscious of motion only within a limited range of speed. Some of the rhythm of a beautiful dance, the graceful leap of a deer, we can see. But an opening flower looks quiet and inert until a motion picture film speeds up its action and shows movements of fascinating grace and precision.

Bird flight, however, must be slowed down if we are to observe its details and understand its technique. From the beginnings of recorded history men have studied and tried to imitate the flight of birds, but there is no record that any man was ever able to learn from observation how a bird flies. Orville Wright wrote: “We got plenty of flying fever from watching the birds, but we got nothing about their secret of balance.” When, through their own genius, the Wright brothers had learned the secret of flight, they realized from a picture of a gliding sea gull that they and the bird were using the same principles and the same type of equipment.

The flight of a bird may appear to be a series of rather haphazard wing beats. But viewed through the eye of a slow motion camera, an intricate bit of organized team play is discernible. Here are many things that will interest the observer, whether aviator, biologist, artist, or nature lover. The fast changes in shapes and positions of wings and feathers in flight are some of the most precise and beautiful motions to be found in the whole realm of nature. Seen through the camera, the seemingly useless flap develops into a whole series of beautifully coordinated actions of the different parts, each with a different function and a different timing, but all combining to give the lift and drive, the balance and direction, that together make up flight.

The biologist will see the reason for the structure of bone and feather as each part of the wing takes, for a split second, some vital and unexpected shape and position. The aviator will find interest in the similarities of design and function in bird and plane. The nature lover will discover new beauty and logic in his favorite subject.

The present study began when, in photographing some American Egrets at their nests, I became aware of the extraordinary beauty of their movements in taking off and landing—movements only partly caught by the eye, or even by motion pictures that slowed them to one-fourth their actual speed. How would these pictures look if they could be slowed to one-eighth speed? It could be done with a Bell & Howell high-speed camera, if some problems of lighting, focusing, and lens mounting could be solved.

The experiment worked beyond all expectation, though, so far as I could learn from the maker of the camera, the problems had not been met before. As the collection of motion pictures grew, some interesting details of wing action began to emerge. Moreover, when I knew what to look for, it became possible to recognize and follow these details with the eye.

In this book are presented some of the facts of bird flight revealed through these motion pictures.

2. The Bird and the Air

Every motion of a bird in flight, every change of shape and position of the feathers, is designed to extract energy from the air and use it to best advantage. When we understand what the wings and feathers are doing while the bird is in flight, we can see that bird and plane use the same principles and the same equipment—wings, propellers, steering and high-lift devices—and use them in much the same way.

Air plays a primary role in bird flight. It is therefore, essential that we examine the more important characteristics of the air and the rudiments of aerodynamics.*

SOME CHARACTERISTICS OF THE AIR

To understand the role of air in bird flight we might think of air as a fluid, with many of the characteristics of fluids and some differences that need not concern us here. Like water, air has weight: 14 cubic feet of air weigh over a pound (.0765 lb. per cu. ft. at sea level at 59° F.). There is so much air above us that at sea level it presses against every surface that it touches—from above, from below, and from all sides—with a pressure of 14.7 pounds to each square inch.

From the weight and pressure of the air a bird develops the power to lift and carry itself forward. To do this successfully the bird must move through the air with the least possible disturbance, for every eddy that it leaves in its wake absorbs energy in its making and cuts down efficiency. So the first essential for flight is a streamlined shape—one that fits itself into the natural lines that the air follows in flowing around an object. This streamlined shape can be seen and photographed by putting an object in a wind tunnel and flowing jets of smoke past it. The smoke jets follow and mark out the streamlines, the path of the moving air stream (Fig. 1).

If the half-sphere shown in Figure 1 is built up to fit and fill in between the lines marked by the smoke, the air will flow around

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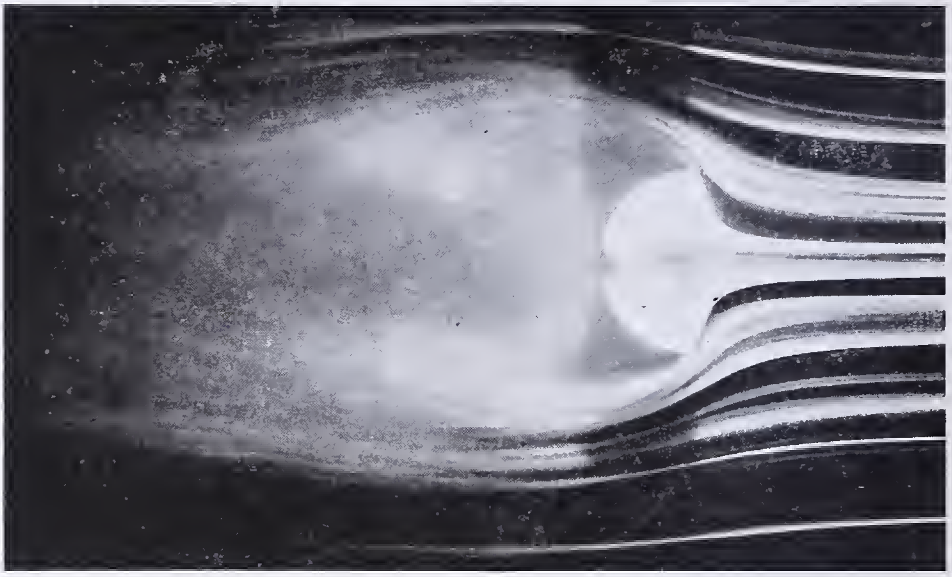
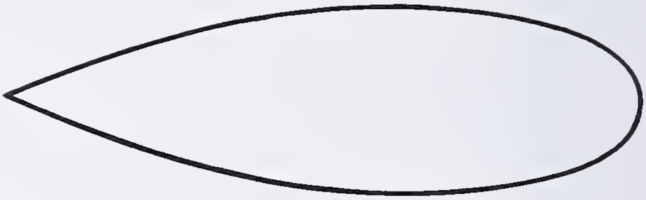
* An excellent introduction to aerodynamics is contained in the Army Manual cited in the list of references.



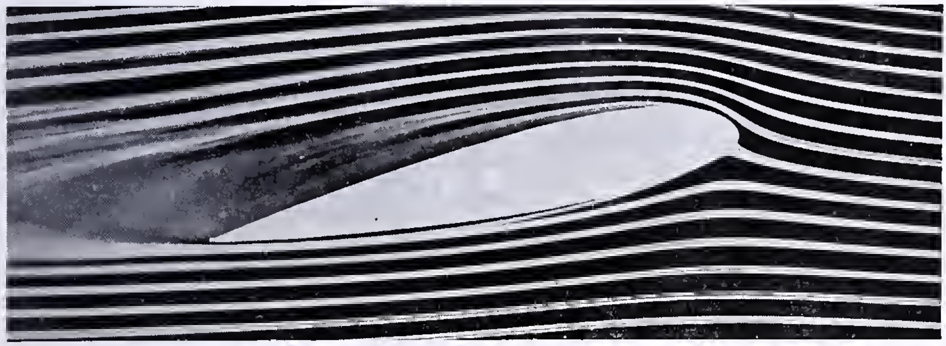
1. The need for streamlining. The white lines are jets of smoke following the moving air stream as it strikes a half-sphere (the white object) in a wind tunnel. The white lines thicken against the face of the half-sphere, showing that there the air is slowed down and compressed, thus increasing the pressure against the face of the obstruction. The smoke lines flow around the object, leaving an apparently empty space behind it, where the air pressure is much reduced—a partial vacuum. The main lines of the smoke stream gradually draw together again at the rear, and then there is increased pressure against the face of the object, with little pressure from behind to counterbalance it. It would take a good deal of power to drive this shape through the air.—Official photograph, courtesy National Advisory Committee for Aeronautics.



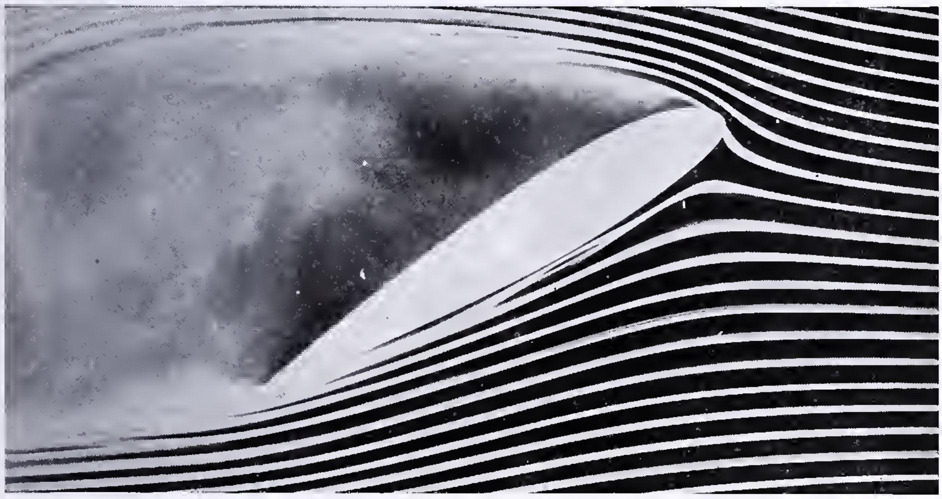
2. Through the use of this streamlined form, the lifting force that makes flight possible can be developed.

Streamlining.

it without leaving a vacuum or building up extra pressure in front. The streamlined form shown in Figure 2, which follows the lines of the smoke streams in Figure 1, can be moved through the air with much less effort and disturbance than the half-sphere of Figure 1.



3. Lift is increased by tilting the wing to deflect the air downward.



4. Too much tilt destroys lift.

Lift.

Official photographs, courtesy National Advisory Committee for Aeronautics.

DEVELOPING LIFT

When air moves past a streamlined surface along the path of its natural streamlines, the pressure on the surface is reduced. This fact is the key to the power of flight, namely, the ability to change and control the air pressure on a wing's surface. Look again at the smoke streams flowing past the half-sphere (Fig. 1). In passing it they do not hug it closely, but are thrown a considerable distance off course above and below it. In the same way, when the air strikes the front, or leading edge, of a streamlined form it is thrown upward and downward, away from the surface. The momentum of this upward and downward deflection reduces the pressure of the air against the streamlined surfaces as it moves past.

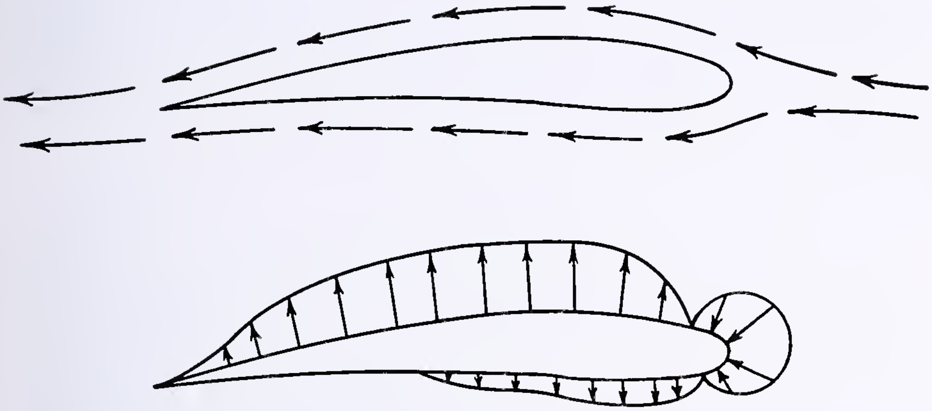
This reduction in pressure can be explained in more exact form by Bernoulli's theorem, which states that in an ideal (i.e. incompressible) fluid the total pressure along the streamlines is constant. Since the total pressure is made up of the static pressure (weight of the fluid) plus the pressure along the streamlines due to the velocity of the motion, each added pound of velocity pressure must result in one pound less of static pressure against the surface.

If the pressure is changed equally on the two surfaces of the wing nothing is gained. If, however, it can be reduced on the upper surface while the upward pressure against the lower surface is maintained or increased, the greater (upward) pressure becomes lifting force, or "lift."

If the lower side of a streamlined form is shortened by flattening it, the air stream over the curved upper surface must go farther, and hence faster, to keep pace with the shorter lower stream and rejoin it at the rear or trailing edge. With its higher velocity the upper stream will put less downward pressure on the upper surface, and the greater upward pressure from below will then exert a lifting force.

Lift can be increased by tilting the wing to deflect the air downward. In this way the pressure against the under side of the wing is increased and the pressure on the upper side is decreased, so that more lift is achieved. The changed course of the smoke streams in Figure 3 shows how the tilt of the wing builds up pressure below and reduces it above. Note that the smoke stream marked g, though it strikes the under side of the wing, is divided and part of it is sucked or forced up into the area of reduced pressure above the wing.

Too much tilt, however, will destroy lift. If the tilt (*angle of attack*) is made too high (Fig. 4), the air stream cannot follow the upper wing surface, but breaks away from it, leaving a partial



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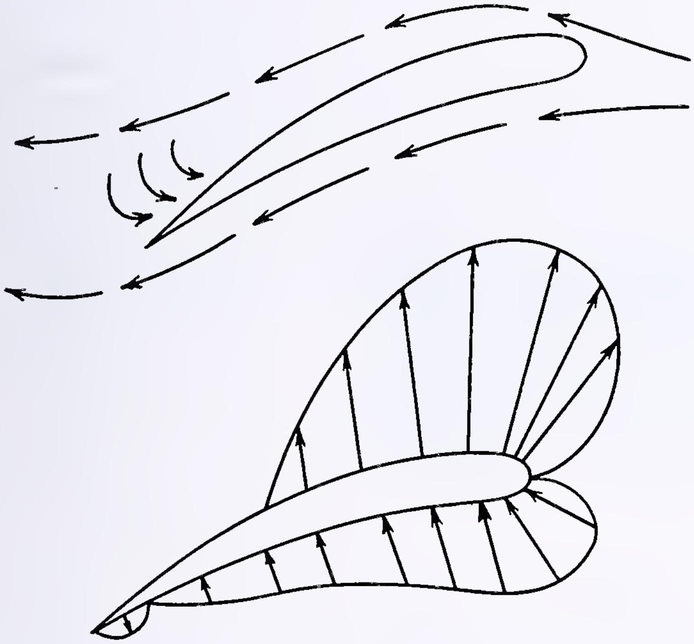


6.

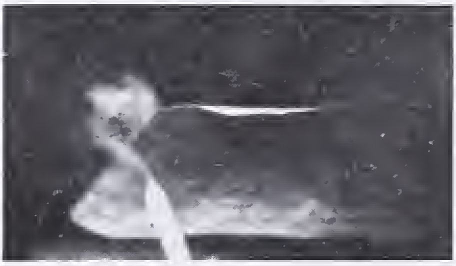
5 and 6. The arrows show the air flow and the direction and amount of pressure changes around the surface of the cross section of a model wing.—Redrawn with permission, from 'Elements of Practical Aerodynamics' by B. Jones, John Wiley and Sons, Inc.

Flow and pressure changes with change in angle of attack.

vacuum into which the air eddies, reducing lift. The angle where this loss of lift begins is called the *stalling angle* or *stalling point.* The wing in Figure 3 has reached this angle. In Figure 4, it is far past the stalling angle and the difference in pressure on the two wing surfaces is changing from lift to backward pressure, or *drag.*

PRESSURE DISTRIBUTION

Changes in pressure on the surface of a wing can be measured by gauges set into the surface. These gauges, which work on the principle of a barometer, show that some parts of the wing supply more lift than others, and that the values of the different parts change with changes in the angle of attack. In Figures 5 and 6 the arrows show the direction and amount of the pressure changes on the surface of the cross section of a model wing. Even with the wing nearly horizontal (Fig. 5), the arrows show that the air pressure has been reduced over most of the upper surface. A change in the angle of attack will completely alter these pressures. The greatest pressure change is on the upper side of the wing (Fig. 6), this surface supplying about three-quarters of the lift.



7. A tip vortex outlined in smoke. A jet of smoke passed from a tube into the air stream of a wind tunnel spirals through the vortex, past a dummy wing tip.

TIP VORTEX

The air passing the under surface of the wing at high pressure has a tendency to whirl up over the rear (trailing) edge into the low pressure area above. Thus some eddies are produced along the edge, the smooth flow of air is broken, and the efficiency of this part of the wing is reduced. As the sketches (Figs. 5, 6) show, the forward face of the upper surface is by far the most efficient part.

This tendency of the air to whirl up behind the wing is especially strong toward the tip, where it whirls up over the edge in a *tip vortex* (Fig. 7). The energy used in making this vortex is a serious drag on the wing. Worse still, the disturbance caused by the eddy spreads inward along the upper surface, breaking the smooth flow of the air and lowering the efficiency of the wing far from the tip.

ASPECT RATIO

To attain the greatest lift a wing must have more than streamlining. It must be as long as possible in order to spread the tip vortexes far apart and allow the greatest possible undisturbed area between them. It must also be wide enough to prevent the eddies at the rear edge from interfering too seriously with the efficient lifting area forward. As noted later in this book, this factor appears to be an important one in the wing efficiency of some of the small birds. The ratio of a wing's length to its width is known as the *aspect ratio.*

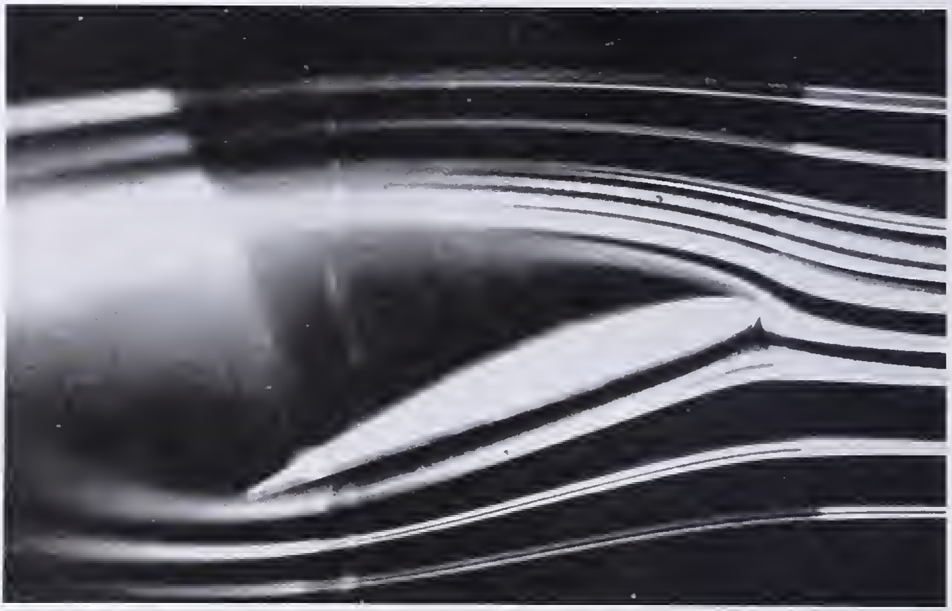
The design of a wing of a plane must be a compromise between the need for strength given by a short wing and the need for the efficiency given by a long wing. So we see the short wing of a fighter plane and the long wing of a bomber; the short wing of a grouse and the long wing of an albatross.

The best design for a wing depends also on the speed for which the plane is built. The wing of a fast-flying plane is slightly convex on the under surface. For a slow-flying bird a concave under surface is more efficient.

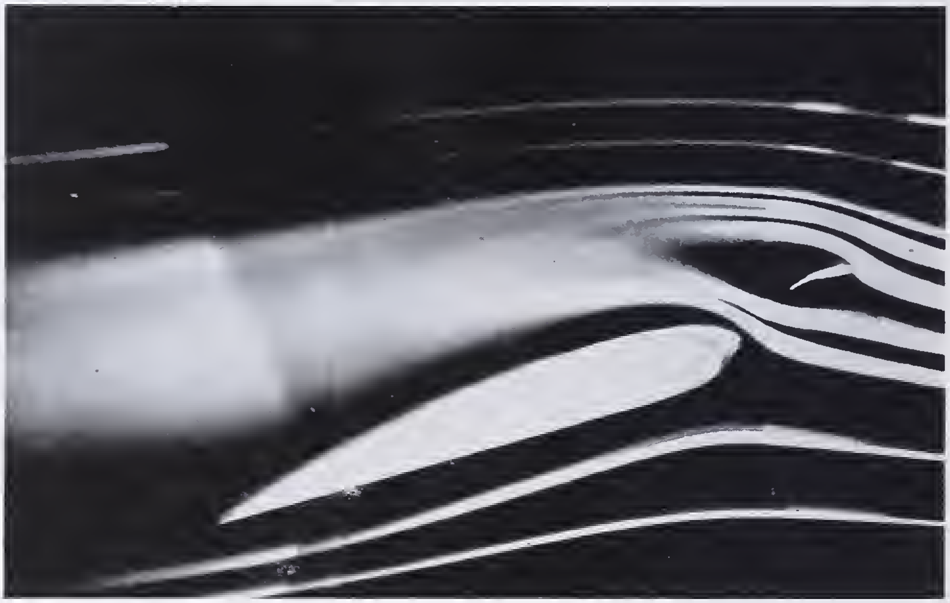
FACTORS THAT AFFECT LIFT AND DRAG

For any given type of wing, lift will increase in about the same proportion as increase in area; thus, twice the area will give about twice the lift. Up to the stalling point, this is true also of the tilt, or *angle of attack.* Thus, twice the angle will give about twice the lift. An increase in speed, however, will give a much sharper increase in lift. Here the increase is approximately proportional to the square of the speed. Thus, three times the speed produces about nine times the lift.

To drive an object through the air takes power. The force of the air opposing the movement of the wing is called *drag.* Like lift, drag is affected by the shape of the wing. Also, drag varies approximately in proportion to the area and the square of the speed. However, it changes much faster than lift does with changes in the angle



8. The wing is past the stalling point, and the air stream, breaking away from the wing's upper surface, has lost its lifting power.



9. The air is following the upper surface again. The wing, though it is still meeting the air-stream at the same angle and the same speed, has regained its lifting power. There is one difference: ahead of the main wing has been placed a small extra airfoil (the small white wing in the black space just above and ahead of the main wing). The two white smoke lines that squeeze into one as they go through the slot between the two wings must flow faster in going through this small space. This added speed reduces the pressure over the wing, with the result shown.

How a slot prevents a stall.

Official photographs, courtesy National Advisory Committee for Aeronautics.

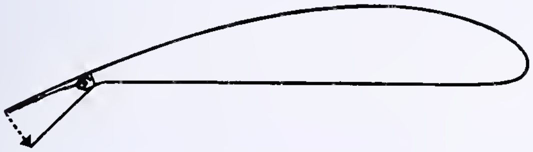
of attack. Up to the stalling point, it changes roughly in proportion to the square of the angle; i.e., three times the angle produces about nine times the drag.

Drag is divided into two types: *profile drag* and *induced drag.* Profile drag is caused by the simple movement of the wing through the air, even at an angle that produces no lift, and is due to friction against the air. Induced drag is caused by any change in pressure against the air—for example, for the purpose of producing lift.

SLOTS AND THEIR PURPOSES

Birds have special devices built into their wings to increase lift and prevent stalling at low speeds. Equipment that functions on the same principles is used by airplanes in taking off and landing. When a wing reaches the stalling point, the stall can be controlled and the lift restored, without changing the angle of attack, by increasing the speed of air flow over the wing. This is accomplished by forcing the air to flow through a slot.

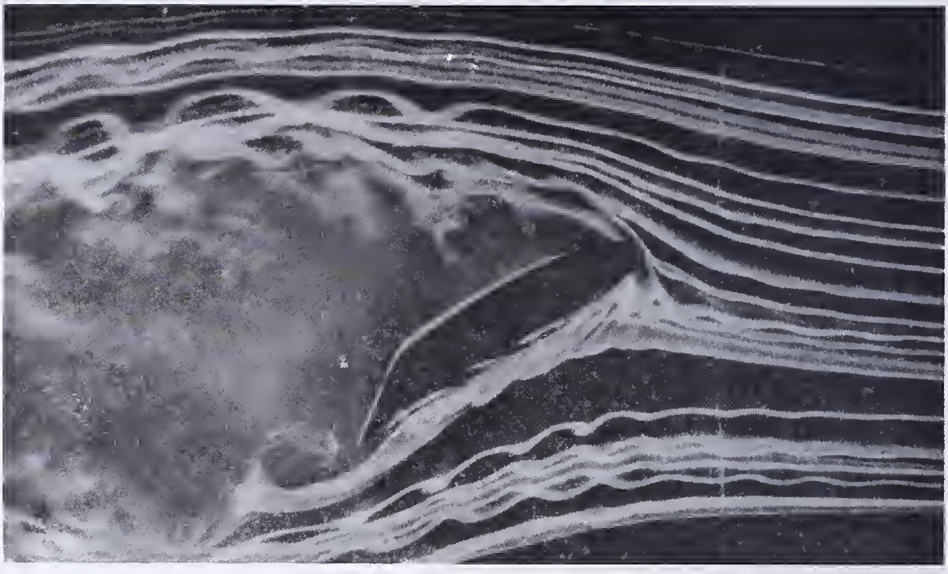
Figures 8 and 9 show how slots can be used to prevent stalling. There are several kinds of slots. Birds use at least four: (1) slots at wing tips; (2) slots in front of the wing, made by the alula or by the first primary; (3) slots behind the wing, between the wing and the tail; (4) slots through the wing, made by lifting the covert feathers.



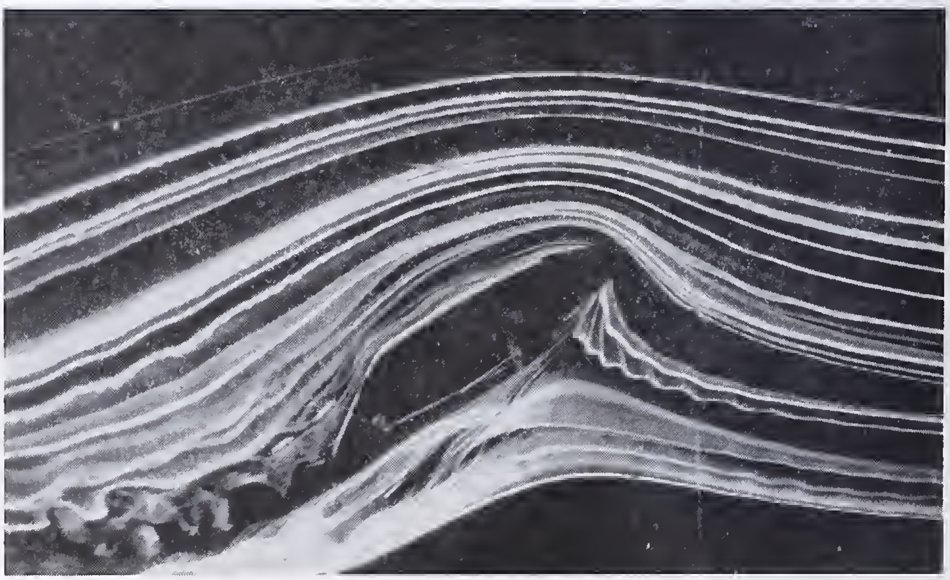
10. A wing section with flap lowered.

FLAPS TO INCREASE LIFT

Another device used by both planes and birds is the *flap,* which increases the lift of the wing for a low-speed landing. In Figures 11 and 12, the rear third of the cross section of the wing is bent sharply downward by means of a flap, hinged to increase the slope (angle of attack) of that part of the wing. Note that in Figure 11 this increase of angle has caused the airflow to break and the wing to stall. In this experimental demonstration, the air flow has been speeded by



11. Separation and stall without boundary-layer control.



12. Flow with boundary-layer control by suction through the wing surface.

The use of the trailing-edge flap.

Official photographs, courtesy National Advisory Committee for Aeronautics.

means of suction through the wing surface (Fig. 12). Thus the smooth flow and lift have been restored. A still more effective type is the split flap, Figure 10, hinged to the under side of the wing so that it can be turned down to increase the angle of the lower surface without changing the upper surface. The flap may increase lift by as much as 70 per cent. It also may increase drag and become an effective brake for landing. The ailerons are another type of flap used chiefly for maintaining balance by increasing or decreasing the lift of one wing in relation to the other wing. The flaps are generally used in unison on both wings to add braking power or lift at the slow speeds of landing or take-off.

3. The Bird's Flying Equipment

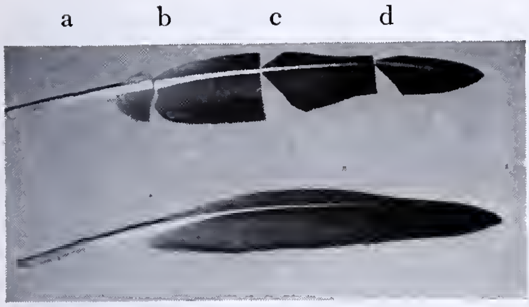
FEATHERS

The key to bird flight is in the design and control of the feathers. In a feather at rest, we see not the shape that will be used in flying but a design that will automatically achieve shapes in response to different pressures from the air. In a single wing beat each of the outer primary feathers goes through a series of different shapes and sizes. When the bird wants to stop, a slight change in pressure against the air gives the feathers a completely different form and a different function. It is demonstrable that a slight change in the position or shape of two key primary feathers can make it nearly impossible for a bird to fly.

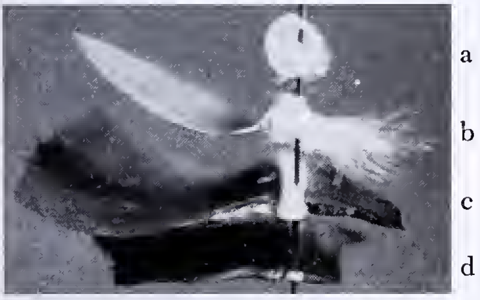
The shape of a feather in action is the result of many different factors: the design of the vane, or web, and the way it responds to air pressure; the design of the barbs, or fibers, that make up the vane and affect its elasticity and shape; and, controlling them all, the design of the quill. The vane is made up of parallel rows of barbs, standing out on each side of the quill. These barbs are like the teeth of a comb in several respects. On some feathers they are flattened and so very flexible that they can easily be bent forward or back toward either end of the feather, but are fairly stiff and rigid against bending up or down. Also, they are placed somewhat apart to allow room for bending. Unlike the teeth of a comb, they do not stand at a right angle to the quill, or base, but are sloped toward the tip of the feather, so that an air current from the direction of the tip can spread them out, and widen the feather.

From each side of these barbs a row of very fine fibers, or barbules, runs out. The fibers from each barb overlap those of the next, like shingles on a roof. They are curved in such a way that as they overlap they grip one another like the tiles on a tile roof, and they are also armed with microscopic hooked barbicels and flanges that interlock.

This structure gives the feather a flexible and almost indestructible surface. If the fibers are pulled apart they automatically inter-



13. Cuts demonstrate the slope of barbs toward the tip.



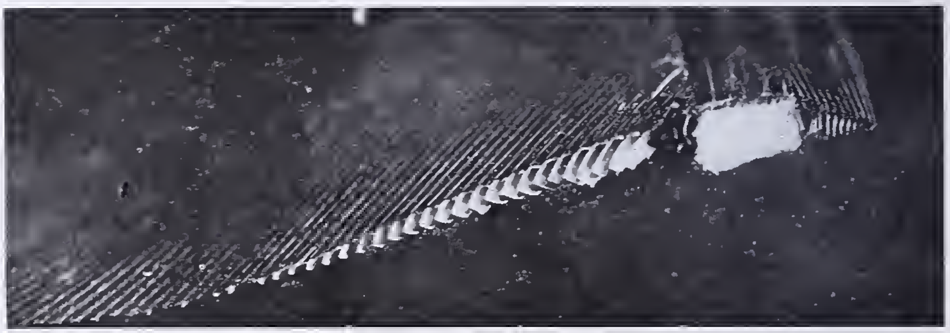
14. Sections at the same loci as above. a. Quill oval for extreme lightness and rigidity. b. Quill rounded, cellular. c. Quill flattened, allowing twist and flexibility. d. Quill flattened, vanes streamlined.

Primary feathers of the Blue Goose.

lock again as they come together, and the surface is again as good as new.

The barbs of the outer primary feathers are much thicker near their bases than at their tips. Thus, they are shaped to give the feather a streamlined cross section, like an airplane propeller. These are the only feathers that strike the air edgewise, and so they are the only ones that need this kind of streamlining. None of the other feathers is streamlined in this way.

The quill of each feather is designed to give the special shape needed for its particular job. The small covert feathers at the front edge of the wing stand perpendicular to the surface to give the wing its proper thickness for streamlining at that point, and at just the right height they bend backward at a right angle to make the smooth surface of the wing. From this L shape they grade through a series of curves to the nearly straight quill of some of the coverts near the wing tip. The cross-sections of the quills vary almost as much; they are round and hollow; square and solid; angular, flat,

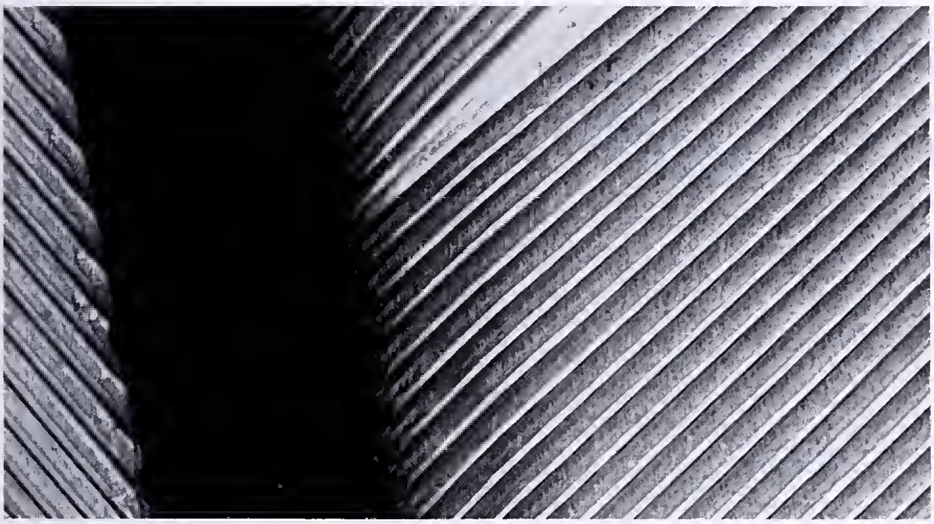


15. Enlarged cross-section of an Osprey primary feather, photographed from slightly above, showing the quill flattened and slightly wedge-shaped. The rear vane is much wider than the front one, which forces the feather to twist against air pressure. The vanes are thickened, giving proper streamlining to the propeller. The thickened barbs are angular, allowing bending without breaking. Note that the barbs are fastened together by barbules at their top edges. Thus the feather has a smooth upper surface.

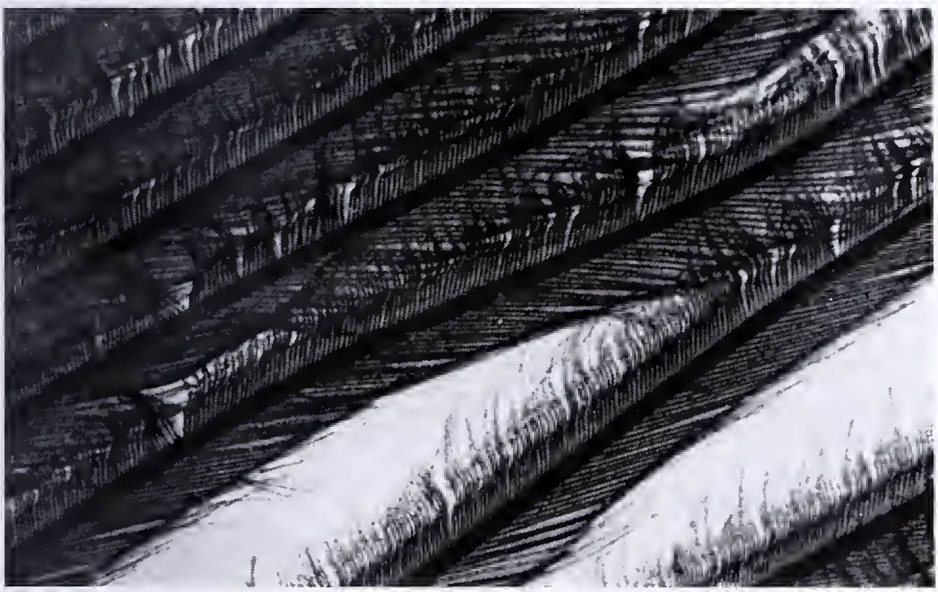
or grooved; thick or thin, depending upon the function and the response to air pressure required of the particular feather. Details of varying structure of vane, quill, barbules, and barbicels are shown in Figures 13 to 17.

Each group of feathers has a different function, and each feather is built to play its special part in the group. The *primary feathers* are on the outer section of the wing, corresponding to the hand, and make up the propeller. The *secondaries,* next in order, on the middle section corresponding to the forearm, make up much of the wing's lifting surface. They differ considerably from the primaries. Few large feathers grow from the inner part of the wing; such feathers would get in the bird's way when the wing was folded. The *tertiary feathers* grow from the elbow. The *scapulars* grow from the scapular membrane, which reaches from the scapula, or shoulder, out to the elbow.

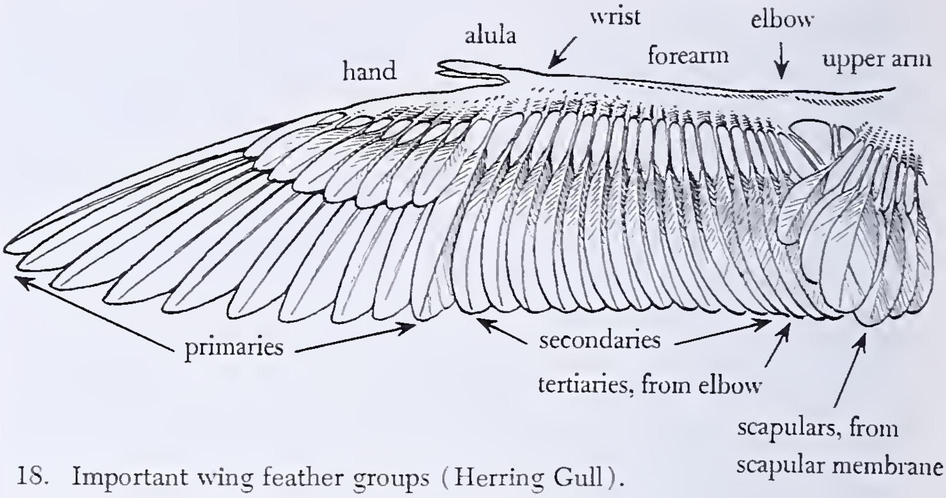
The movement of the primary and secondary feathers is partly controlled by a strong elastic membrane, the *patagium,* which runs along the front of the wing from shoulder to wrist, and along its back edge from the outer bone tip to the elbow. The feathers along the front edge of the wing grow from this membrane, which holds them in a position to give the wing a straight, streamlined edge, even when the elbow is partly bent (Fig. 18).



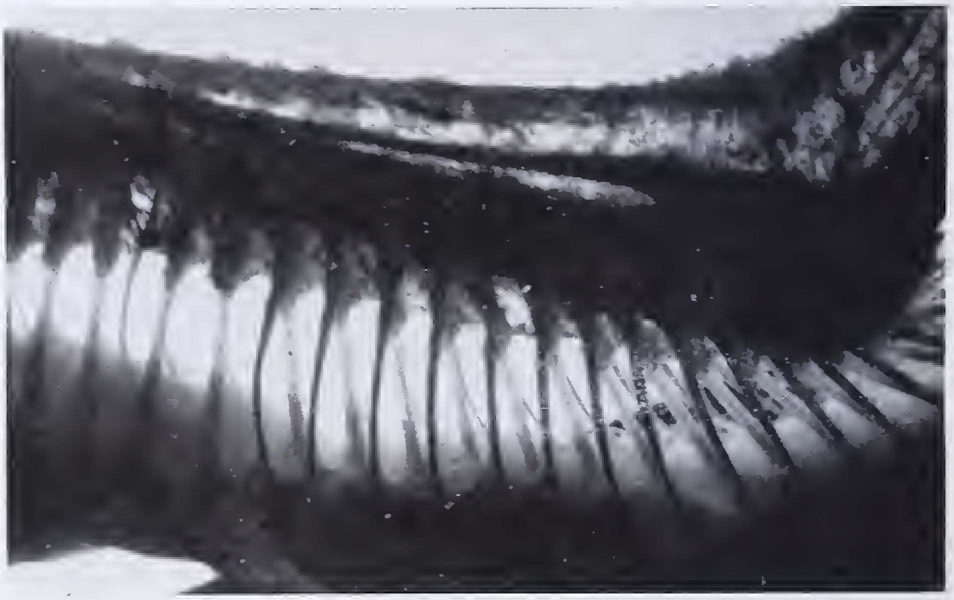
16. Enlarged view of a vane from above, showing barbs (white lines) running obliquely from the quill, with tiny barbules intermeshed between them.



17. Enlarged vane, showing barbs, barbules, and barbicels. Two of the barbs (dark lines) have been separated to show how the barbules run obliquely from them, thus giving to the vane a greater elasticity than would be possible if they were set at right angles. Note that the right-hand row of barbules curves upward; the left row, downward and then up. As they overlap, they interlock. The left row has a double curve, down and then up, so that it can slide into place over the other row easily if the two become separated. The barbicels can be seen faintly on both rows of barbules.



18. Important wing feather groups (Herring Gull).

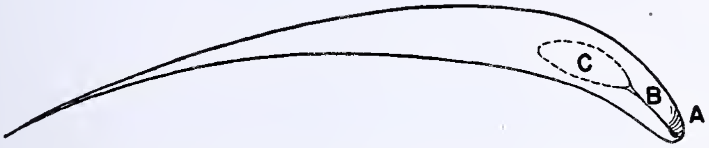


19. Forearm section of a Herring Gull s wing. Note that the covert and secondary feathers grow in pairs, the curved quills of the covert feathers arching over the straight quills of the secondaries, to give the proper streamlining. Each pair of feathers is fastened together at the base, resting against the bone and running out through the membrane, which partly controls their positions (see Fig. 23). The tertiary feathers, growing from the elbow, point in toward the body. The dark line running out from the base of the upper arm, through the membrane, to the wrist, is the tendon of the extensor muscle that runs over the wrist, like a pulley rope, to the hand, or outer wing. When the elbow is straightened this tendon is tightened, and the outer wing is thus automatically extended.

THE WING

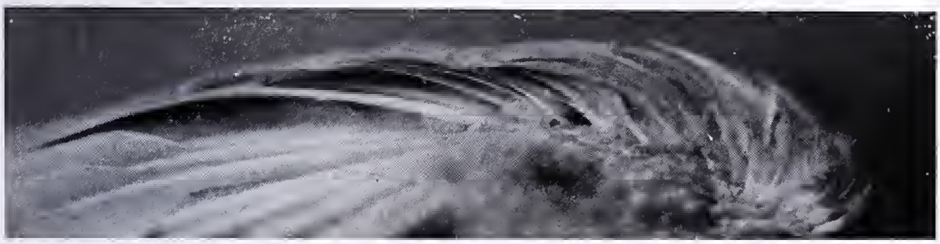
A bird's wing acts not as a single piece of flying equipment but as several pieces, each having a different function and movement.

The inner half of the wing, from shoulder to wrist, corresponds to the wing of an airplane. It moves comparatively little during flight but, like the wing of a plane, supplies the necessary lift. The shoulder joint is so built that when the wing is extended it is automatically held at the proper angle to give lift, sloping down-



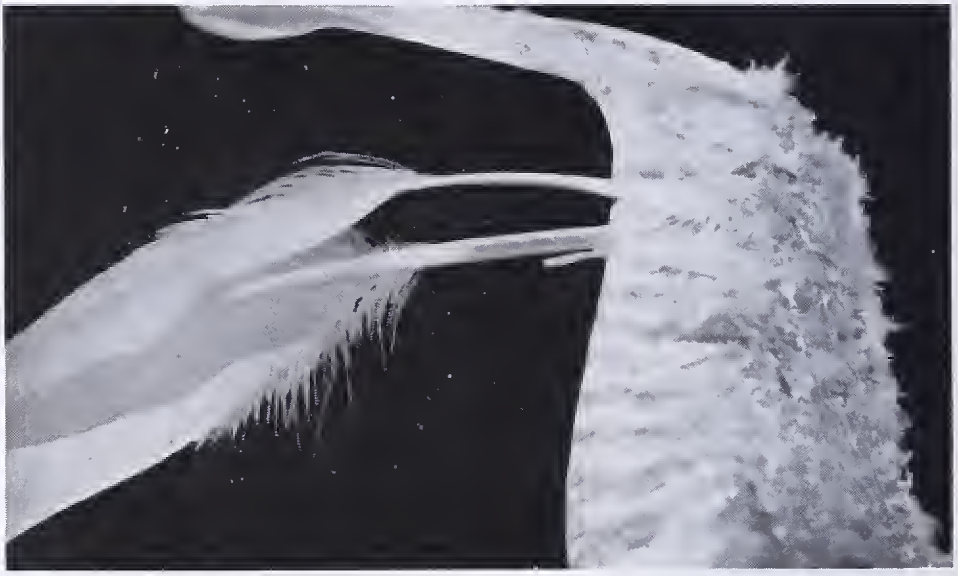
20. Cross section of a Herring Gull's wing (from a plaster cast). The front edge is streamlined by the tiny covert feathers (A), which stand up from the membrane (patagium, B) at right angles, to give the front edge its proper streamlined thickness, then turn sharply backward to make their outer ends form the surface of the wing. The position of the forearm is indicated by area C.

21. Covert feather (enlarged) from the front edge of a Raven's wing, showing curve. One vane has been removed to show the quill in a natural, vertical position.



22. Cross section of a pigeon's forearm, showing the arrangement of feathers to give a streamlined shape. At the rear, the large covert feathers arch over the secondaries; in front, the small covert feathers stand up straight, then curve backward.

The streamlining of the wing.



23. A Herring Gull's forearm, showing the relative arrangement of secondary and covert feathers which produces the streamlined wing shape. The two feathers come through the membrane at different levels, but their bases are joined under it.

ward from the front to the rear. The inner half of the wing is thickened and streamlined like the wing of an airplane, to give it the greatest lifting efficiency. Each feather is shaped and set in the wing differently to fill its place and function, so that when all are fitted together they produce the perfect wing (Fig. 19). Figures 20 to 23 show further details of wing structure.

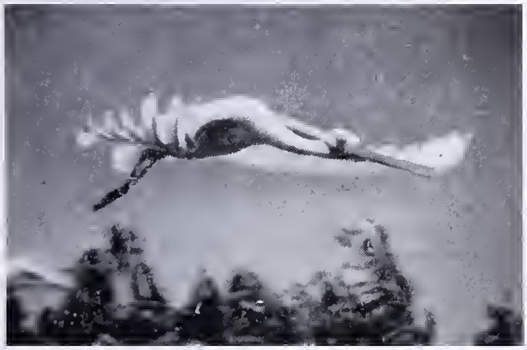
THE PROPELLER

The outer half of a bird's wing, starting at the wrist, constitutes the propeller. This half of the wing differs radically in design and function from the inner half.

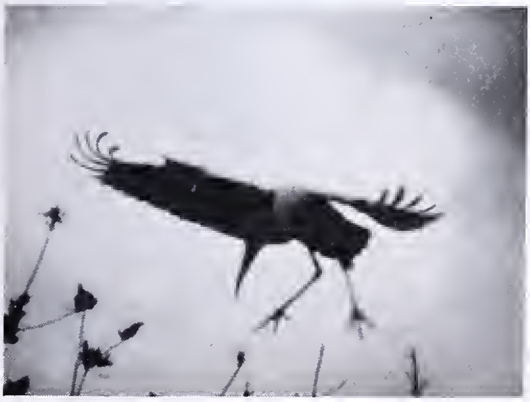
The propeller blade of an airplane may be compared to a wing so placed that its lift carries the plane forward instead of upward. To do this the propeller surface must face and move in a different direction from the lifting wings. So the propeller is designed to whirl at a right angle to the plane's line of flight.

As the propeller whirls, the outer ends of the blades must go through a wider arc than the inner ends near the hub, and so must go faster. This means that, all the way from tip to hub, each fraction of the blade moves faster than its inner neighbor. And each fraction, with its different velocity, will have a different amount of forward drive, or lift, than its inner neighbor. So, if the blade is set at an angle efficient for the speed at the tip, this position will then be inefficient for the speeds of the other parts. To be efficient, the blade must be designed with its angle, or pitch, constantly changing from hub to tip, in order to give an even amount of forward drive through its whole length.

A bird's propeller feathers achieve this changing pitch, or twist, by an ingenious design of quill and vanes which gives the proper angle in response to the pressure of the air. An airplane propeller whirls in one direction. A bird's propeller can swing through only a semicircle; it must then return to its former position and start over again, completely changing its shape and pitch while doing so. It must be ready to go into reverse or to become a helicopter blade to lift the bird straight upward. If the bird wants to glide, the pro-

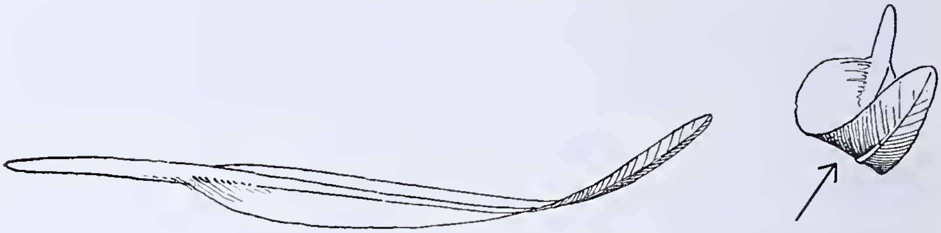


24. Propeller blades of a Roseate Spoonbill. On the down stroke of the wing the pressure against the air twists the wide rear vanes of the outer primary feathers, spreading them apart and giving them the shape and function of propeller blades.

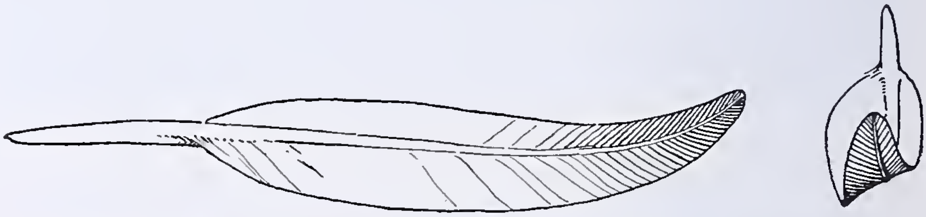


25. Propellers of a Wood Ibis in the reverse.

Propellers in action.

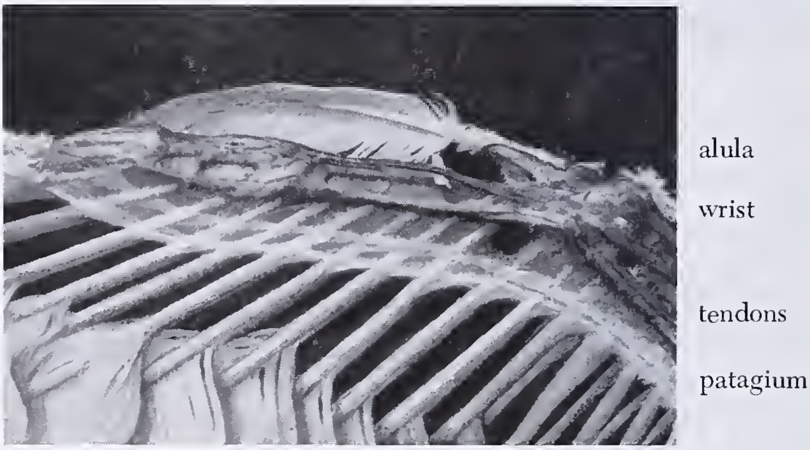


26 and 27. Detail illustrating action on down stroke as shown in Figure 24. 26. View from rear. 27. End view. The arrow indicates the direction of the air pressure.

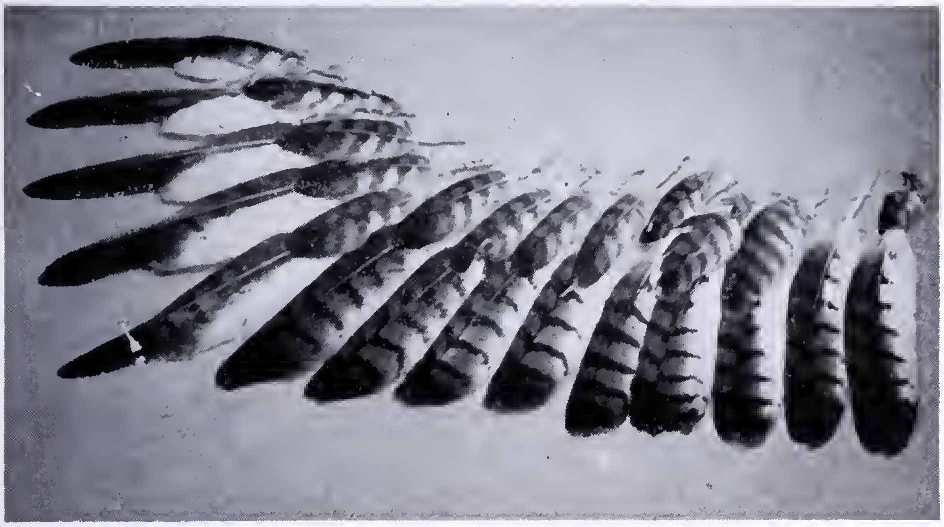


28 and 29. Detail illustrating action with propellers reversed as shown in Figure 25. 28. Start of stroke, feather slightly rotated, back edge downward. 29. Resulting shape, end view.

Changes of shape in primaries.



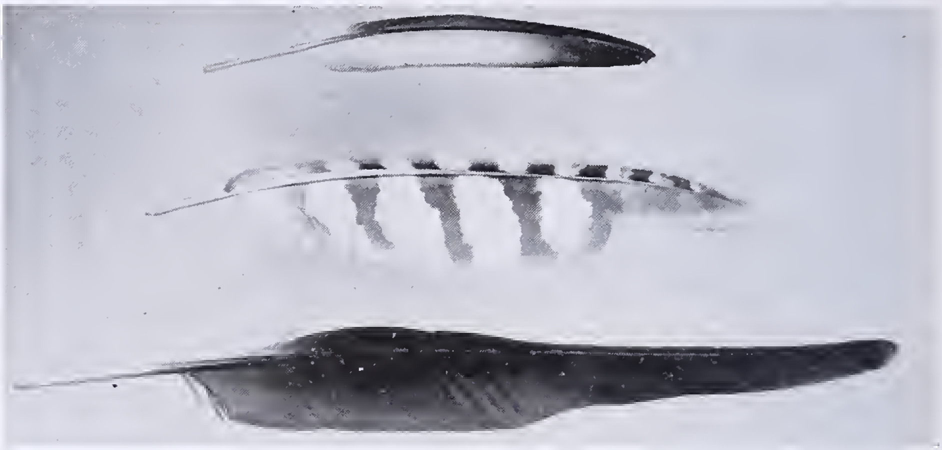
30. Control elements of the Herring Gull's propeller. (See text)



31. Flight feathers from the wing of a Rough-legged Hawk, showing comparative structure of the primaries. The first primary is slender and notched to form a slot and first propeller blade; the next four primaries are deeply notched, the outer halves forming separate propeller blades, with the inner halves overlapping to form the surface of the main propeller; the next five primaries are cut diagonally across the ends and overlap to form the smooth rear edge of the propeller.

peller changes its function and becomes merely a part of the main lifting wing, with the added job of keeping the bird balanced. It must, of course, take the right shape for each job automatically in response to changes in air pressure (Fig. 24).

The propeller blades of the bird can be thrown into reverse, as shown in Figure 25. The quills of the outer primary feathers curve slightly downward when not in use. Pressure against either side of the curve tends to twist the quills. On a normal down stroke the air pressure helps to twist them into propellers, but if they are slightly rotated, so that the upward pressure of the air begins to strike their rear edges, the effect is to twist the quills forward while still twisting the wide rear vanes upward. Then the two twisting tendencies counterbalance each other, and instead of twisting, the feather is bent straight upward, so that its full surface strikes against the air to act as a brake or as a propeller in reverse. Some birds can actually fly backward by using this technique. Figures 26 to 29 show details of the position of the feathers in these strokes.

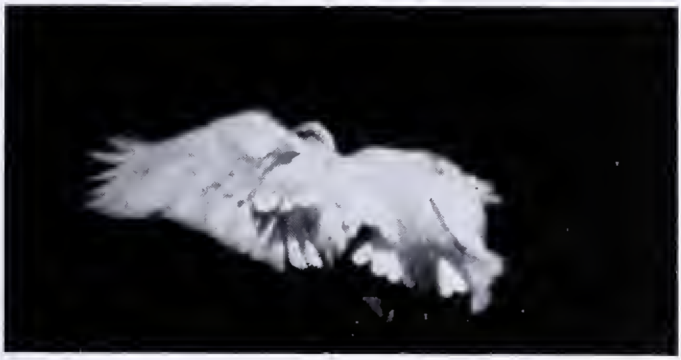


32. A group of primary feathers, showing different types of notching. Top to bottom: 1) Common Pigeon, slight notch on front vane; 2) Great Horned Owl, deeply notched on rear vane; 3) Northern Raven, notched both front and rear. Note on all the feathers the wide rear vane, which allows twisting against air pressure.

The construction and design that permit these wing movements are illustrated in Figures 30 to 33. The alula is controlled by three muscles and can be moved up, down, or forward. It is used to form a slot in front of the wing when needed. The alula is essential in slow flight. Some birds cannot take off or land without it.

The hand is controlled by tendons running out over the wrist like tiller ropes. Three tendons can be seen in Figure 30 as lines to the right of the wrist. These tendons can move the hand and finger within a limited range, up or down and forward or back.

The first primary feather is fastened tightly to the outer finger joint and is controlled by it. It is the only feather with this individual control. The other primaries and the secondaries are controlled, not individually but in groups, by the motion of the joints, and by the elastic membrane running from the first primary back to the elbow (Figs. 19, 30). By flexion and extension of the joints, this membrane controlling the direction and angles of the feathers is tightened or relaxed and the secondaries are slightly rotated. The membrane is attached to, and apparently controlled by, the muscles and tendons of the forearm and hand. Tied together in this way, the feathers must act together. Thus the surface curves of the wing achieve continuity and flexibility.



33. An American Egret, in landing, uses slots at the wing tips and between wing and tail. The covert feathers raised on the wing surface probably allow air to pass through, producing the effect of a slot in the wing. These raised feathers, with the downward sloping secondaries below them, also have the effect of a flap—they increase lift and brake power.

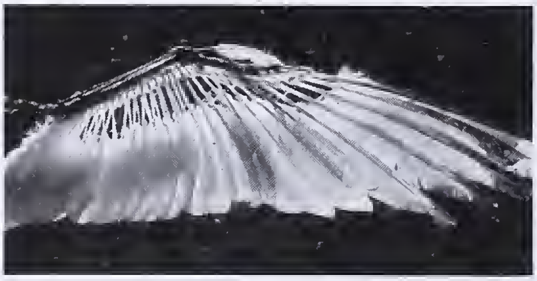
The first primary feather of many birds is more flexible than the others and tends to bend outward under pressure of the air. Thus a long slot is opened in front of the wing when it is needed. The next two or three primaries of many birds are notched in varying degrees, so that slots can be opened or closed as needed (Figs. 31–33).

WING ADAPTATIONS

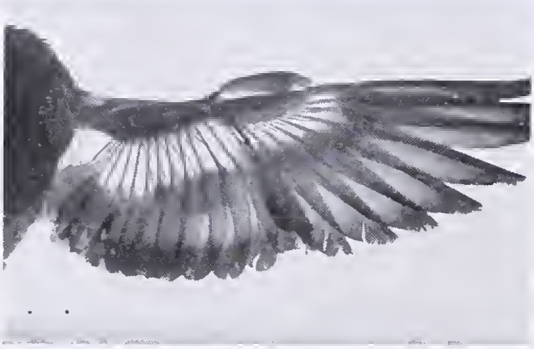
Like the bird's feathers, the machinery that uses them is designed to do its work simply and as nearly automatically as possible. Moreover, it is adapted to the living-habits of the species. A comparison of the wings of the Herring Gull and the pigeon will illustrate these special adaptations.

The gull, living in an environment of great distances and fairly reliable air currents, depends upon gliding for most of its travel. So its wing is light, long, and narrow, an efficient shape for gliding, but too long to be controlled easily by its muscles (Fig. 34). The gull is a good glider, but a weak flier.

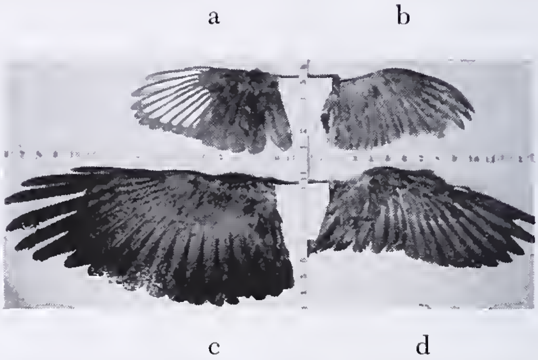
In contrast, the pigeon's wing (Fig. 35) is built for a strong flier. It is not a good wing for gliding, and the pigeon cannot glide at the low speed of the gull. The aspect ratio of its wing, that is, the ratio of length to width, is only about two-thirds that of a gull's wing. The forearm of the pigeon's wing is thickly muscular, the gull's



34. Wing of a Herring Gull, with the skin removed; a glider's wing, with long, slender bones and thin, elastic tendons pulled like tiller ropes by the short muscles at their roots.

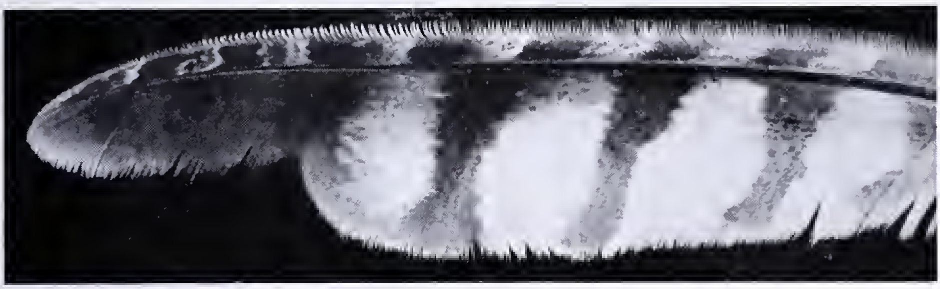


35. Wing of a pigeon, short and heavy-muscled for strong flying.



36. Some different wing types. a. Magpie wing, short, adapted for use in thick cover; note the short primary. b. Wing of Ruffed Grouse, short and broad, the primaries curved backward, adapted to flying through brush. c. Crow. d. Wing of Black Duck, a more efficient wing, with higher aspect ratio; no adaptation to brush flying needed.

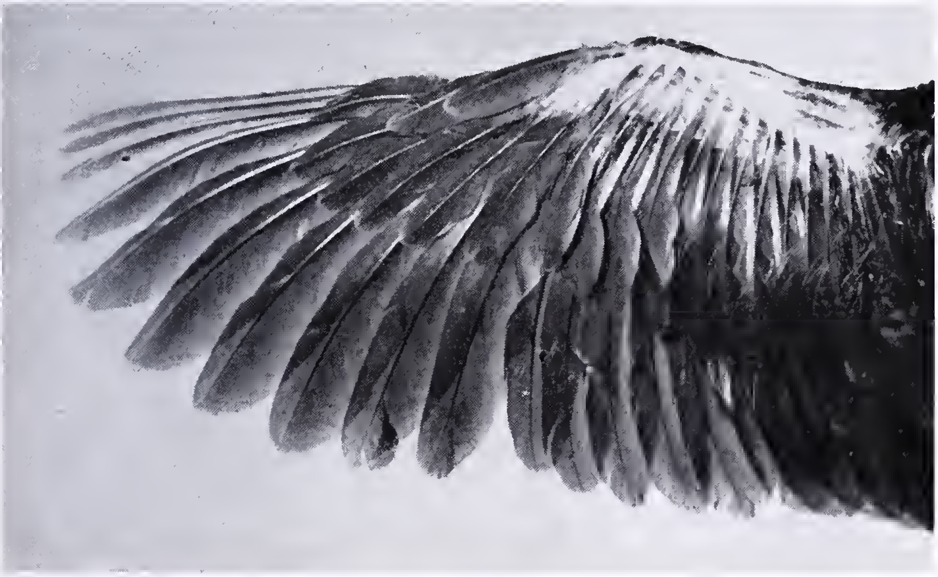
Some wing types.



37. Primary feather of a Western Horned Owl, fringed along the edge, to minimize air turbulence and muffle sound.

thin, its tendons controlled by short muscles of the upper arm. While the gull's primary feathers rest loosely against the hand, allowing a sensitive control by the membrane for accurate adjustment to the air in gliding, the pigeon's primary feathers are fastened tight against the back of the hand to form a strong propeller.

Figures 36--38 show further wing and feather adaptations.



38. In front of the main primaries, the Woodcock has three feathers with almost no vanes. They make a whistling sound, probably used for guidance by other Woodcocks in night flying.

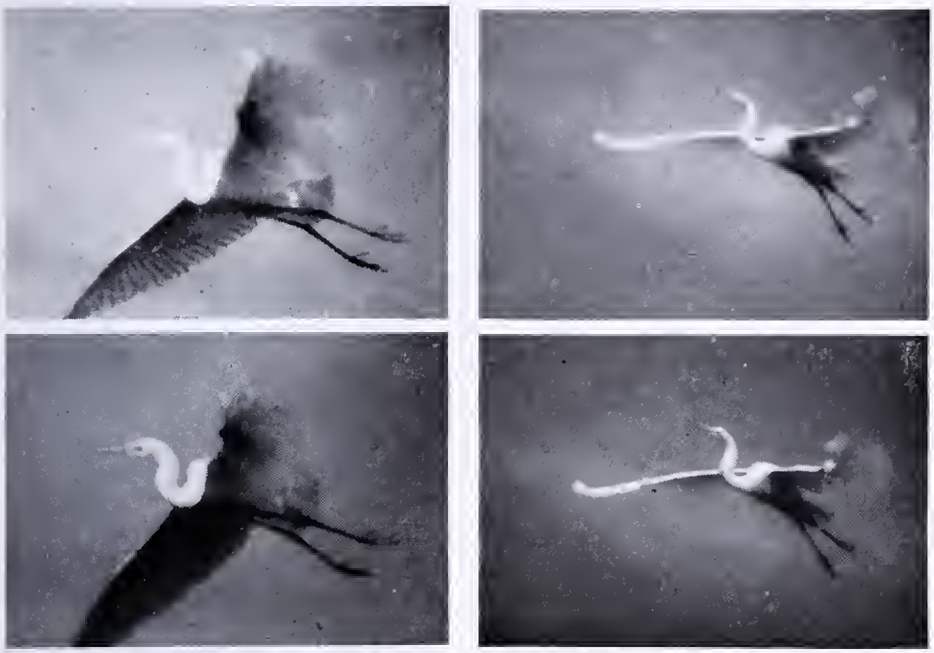
4. Flight

THE FIRST STEP in understanding bird flight is to think of the bird as a living airplane. In such a comparison it should be remembered that the wing of the bird is not a single piece of equipment, but basically two; for the inner half of the wing corresponds to the wing of a plane and the outer half of the wing functions as a propeller.

I once saw an American Egret flying low over some bushes where there was not room for a full wing beat. The bird held the inner part of each wing extended horizontally, but motionless, and beat the outer part up and down from the wrist, thus demonstrating perfectly the true function of each part of the wing. The inner part was lifting, the outer part driving. However, a propeller must move very fast to develop its driving power, and to move the outer half of the wing fast enough, as did the Egret, requires great effort. It can be moved much more efficiently when the powerful breast muscles sweep the whole wing up and down from the shoulder. This is the chief reason that the inner wing moves in flight; it is merely the handle that moves the propeller. Its movement is much less than that of the propeller, and the timing is different.

The path of the wing tip on the down stroke is downward and forward; it is driven forward by the propeller and pulls the bird along after it. On the up stroke the wing tip moves upward and backward. By thus thrusting backward against the air it still drives the bird forward. The bird's need dictates the amount of forward and backward motion. Under pressure, as in taking off, the strong drive of the propellers gives the wing tip a path more nearly horizontal than vertical, but in leisurely flight the motion is nearly vertical. By maintaining the proper angle, the inner wing supports the bird's weight throughout the entire wing beat. This angle is constantly adjusted to maintain a steady lifting force. It increases as the wing rises away from the air stream, and flattens again as the downward beat tends to increase pressure against the air.

Between the inner and outer halves of the wing, in the area of the wrist, there is a section where the wing twists from the lifting angle of the inner half to the driving angle of the propeller. This



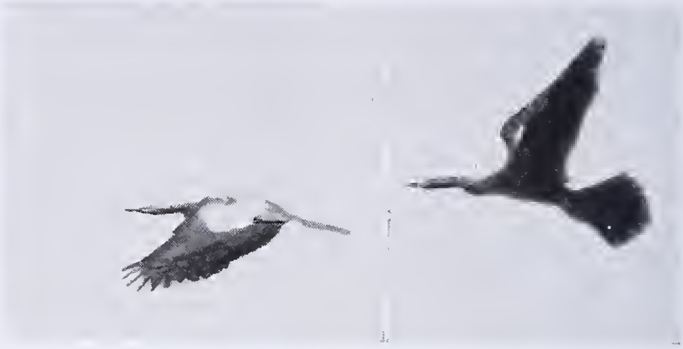
39 – 40 41 – 42

What happens when a bird beats its wings.

The pictures on the left show how the primary feathers of the American Egret twist into shape as propellers. The bird beats its left wing faster to make a turn, and the air drives the feathers forward. Figure 39, midstroke; 40, 1/128 second later. 41, midstroke; 42, 1/128 second later.

section, striking vertically downward against the air on the down stroke, must supply considerable lift by direct downward motion against the air. Aerodynamically this is not the most efficient way of producing lift, but since this area of changing angles cannot be avoided, the wing is used to the best advantage within its limitations.

While it is probably true that no two kinds of bird fly in just the same way, all must use the same principles of aerodynamics. The differences in flight appear to be chiefly a matter of using the type of wing best adapted to the bird's manner of life. The albatross, the vulture, and the Herring Gull, for example, are all gliders, but in their search for food they encounter different types of air currents and require different kinds of wings to meet these various conditions. Again, the Ruffed Grouse must have a wing that



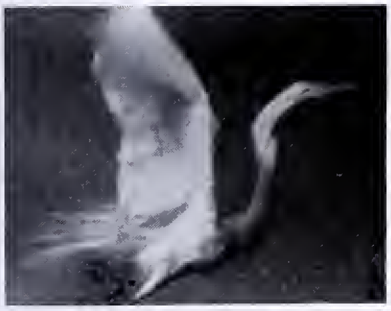
43. Wing positions of an Anhinga at the start and finish (right to left) of the same beat. The wings have been driven forward by the propeller feathers, and the bird is pulled along with them.

can be used in dense woods. It is not the most efficient wing aerodynamically, but is adapted to the conditions under which it is used.

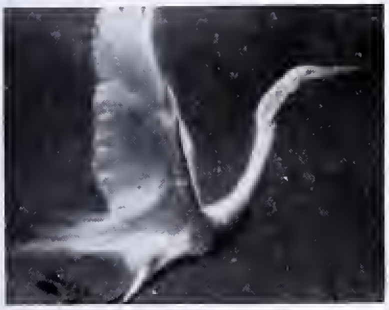
The clearest demonstration of the principles of bird flight is given by some of the big slow flying birds, as shown in the illustrations beginning with Figure 39. Each series of flight pictures is selected from phases of a single wing beat, as recorded by a slow motion camera.

The forward movement of a bird during a single wing beat is shown in Figures 49 to 53, and may be measured by the bird's position in relation to the sloping stick at the lower right of the pictures. The first three pictures (Figs. 49–51) show the down stroke; the last two, the up stroke. The bird, an American Egret, keeps to a nearly level course past the stick throughout the wing beat, showing that the wings provide support even during the up stroke, as proved by Figure 52, where the rear edge of the upward moving wing is still arched upward by the lift of the air. Progress is about the same on the down stroke as on the up stroke, a fact that suggests that the propeller may give a good deal of forward drive on the up stroke, even in leisurely flight. The time interval is about the same, namely, 14/128 second on the down stroke and 16/128 second on the up stroke.

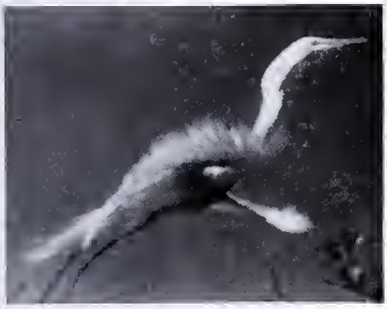
In the second series (Figs. 54–58) the stages in a wing beat are shown from the rear. At midstroke (Fig. 54) the inner halves of the wings, which supply the lift, slope up from back to front, with their white upper surfaces showing. The outer halves, rotating to function as propellers, show their shaded undersides, which appear dark. The



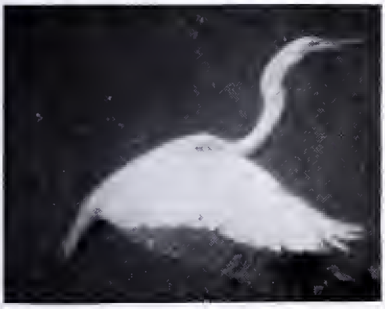
44. End of up stroke. The speed of the wing motion blurs the picture.



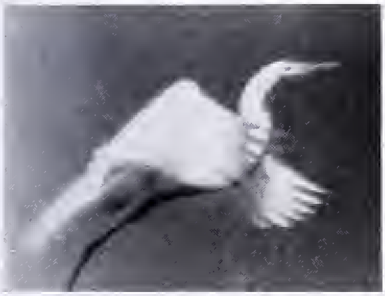
45. 1/32 second (4 frames) later. Start of down stroke. Pressure against the air twists the primaries into propellers, then drives them forward.



46. 1/14 second (9 frames) later. At midstroke the functional angles of the wing stand out. The inner wing slopes up from back to front. The primary feathers of the outer wing slope up from front to back. Thus the wing supplies its lift and drive.

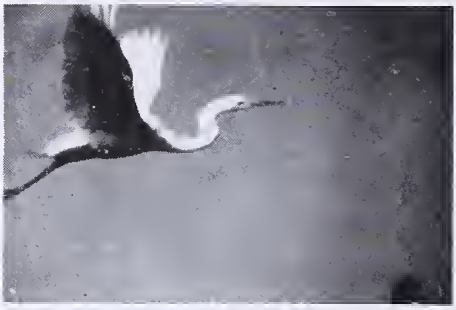


47. 1/21 second (6 frames) later. End of down stroke. The propellers have driven the wings forward by a full body length during this down stroke.

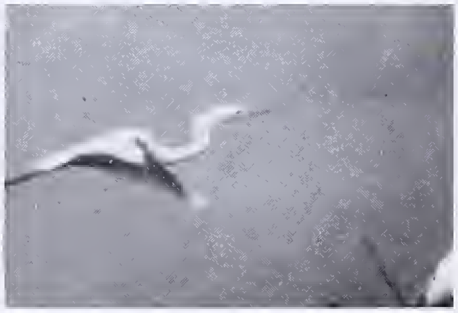


48. 1/21 second (6 frames) later. Start of up stroke. The back edge of the wing is arched upward by the lift of the air. It is still supporting the bird. The wing tips, sweeping backward against the air, still supply some forward drive, as shown by the forward bend of the feathers. The angle of their twist shows that they are probably supplying some lift too.

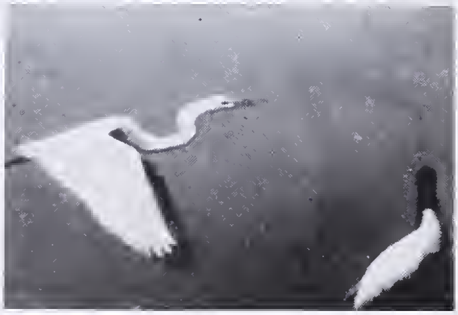
Lifting functions of the wing of an American Egret.
Photographed at 128 frames per second.



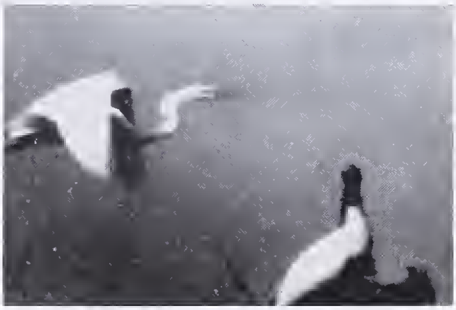
49. Beginning the down stroke (4 frames after start).



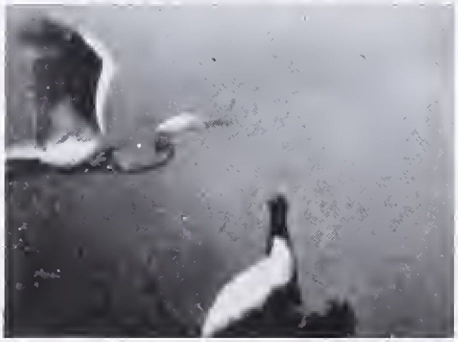
50. Midstroke (7 frames later).



51. End of down stroke (7 frames later).



52. Halfway through up stroke (8 frames later).



53. Ready for next down stroke (8 frames later).

The progress of a wing beat in an American Egret.

Photographed at 128 frames per second.

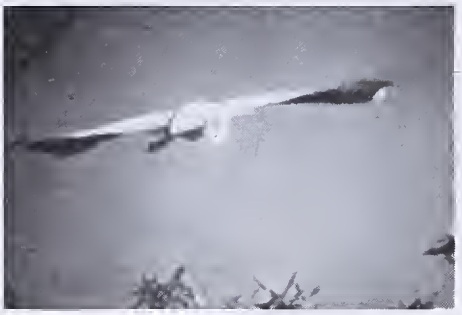
primary feather tips are bent upward in front of the wing and do not show. The U-shaped curve below the wings is the bird's neck. At the next stage (Fig. 55) the inner halves of the wings are at the end of the down stroke, and the outer halves are still sweeping downward. The functioning of the inner and outer halves is timed differently. In the next picture (Fig. 56) the inner halves have started the up stroke, rising to the horizontal. The outer halves are just finishing the down stroke. The right wing tip is still bent outward by its pressure against the air. In the next picture the inner halves have risen to the top of their stroke (Fig. 57) and pause momentarily—still supporting the bird—while the outer halves sweep up and back. The inner halves move very little during the wing beat and never lose their slope upward to the front. In the last picture (Fig. 58) the wings are at the top of the stroke, ready for the next down stroke. In 1/8 second more they will be back in the first position (Fig. 54).

SOME FLIGHT SPECIALIZATIONS

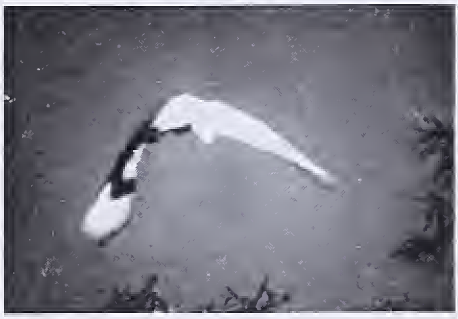
The wing of the hummingbird is especially adapted to the flight and living habits of this tiny bird. The wing seems to be all propeller, set on a swivel joint at the shoulder. It can be rotated to drive the bird forward, upward, or backward, or to permit hovering in the air, like a helicopter. This kind of wing is not the most efficient type for flight, and sustained travel with such wings would probably require more energy than could be put forth by even a bird much larger than he hummingbird. However, it is an ideal wing for the hummingbird's purposes. (See Figures 59 and 60.)

Stroboscopic photographs taken by Professor H. E. Edgerton show a somewhat similar type of wing and flight in bats and some insects. It is an ideal type of wing for very small, light fliers, for it gives high maneuverability and control. However, it does not meet the needs of larger, heavier fliers, which require greater aerodynamic efficiency. As a bird increases in size its body and weight increase in three dimensions, while the lifting area of the wings increases in only two. Thus as the size of the bird increases, the need for efficiency in flight becomes ever more essential.

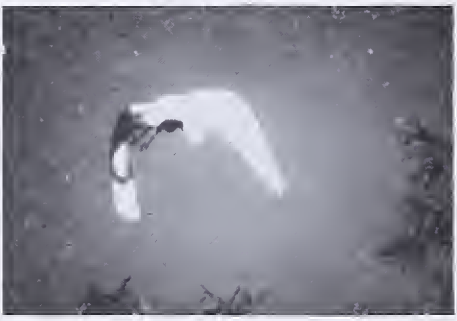
Some birds, such as woodpeckers, nuthatches, and finches, fly with an undulating motion; they shoot upward with a few fast wing beats and then coast downward on set wings. This ability



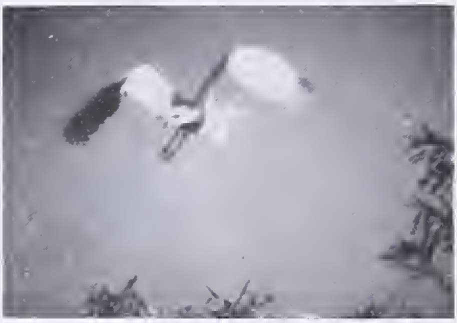
54. Midstroke.



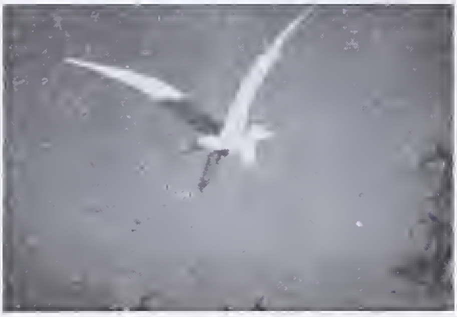
55. 1/18 second (7 frames) later.



56. 1/25 second (5 frames) later.

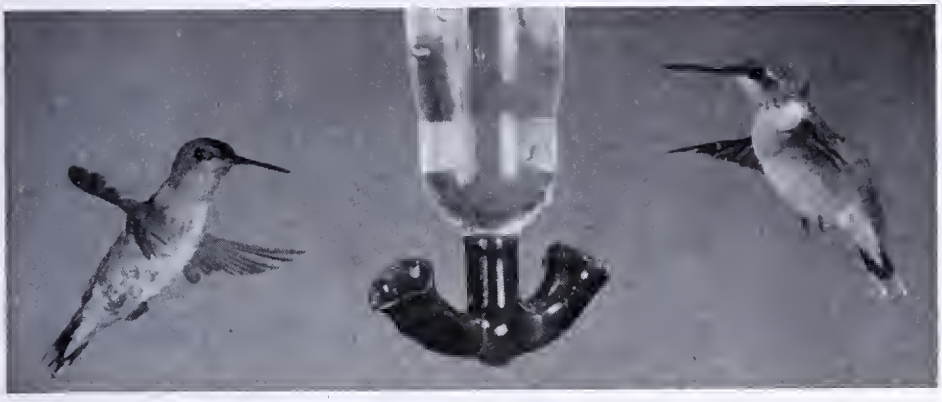


57. 1/18 second later.

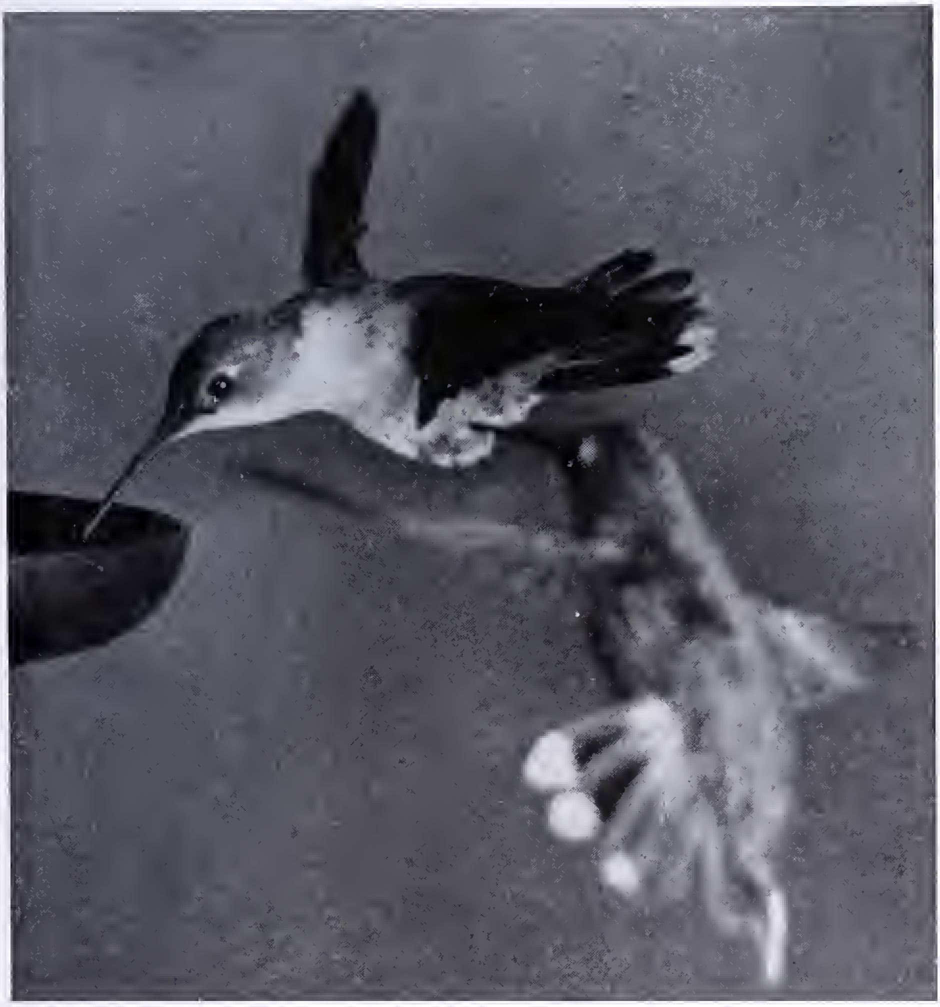


58. 1/25 second later.

Stages in a wing beat of an American Egret, as photographed from the rear.



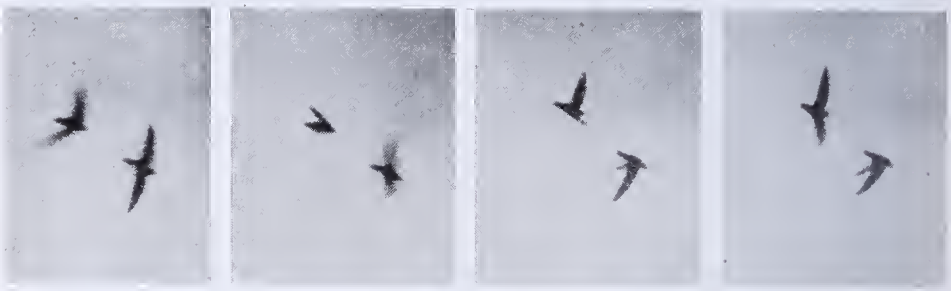
59. Allowing it to hover in the air, the hummingbird's wing is ideally suited to the bird's life habits.



60. The hummingbird's wing seems to be all propeller.

Stroboscopic photographs of the Ruby-throated Hummingbird.

Photographs courtesy Prof. H. E. Edgerton.

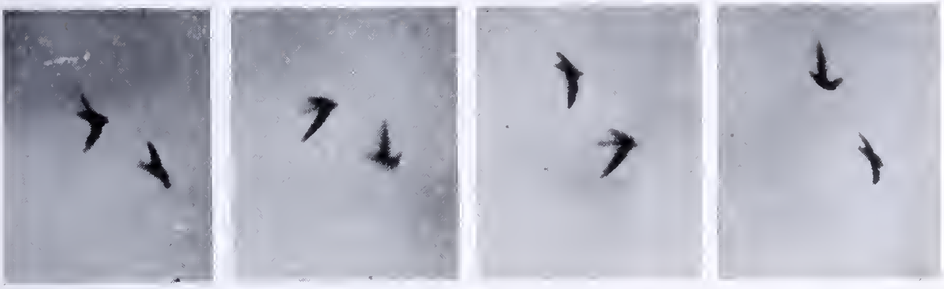


61 – 68. Another variation in flight technique: The Chimney Swift. Photographs taken at intervals of 1/21, 1/21, 1/64, 1/16, 1/21, 1/21, and 1/21 second.

to glide into landing position must simplify some problems for a bird that wants to land upright against a tree trunk or upside down beneath a twig.

The observer who has some experience in following bird flight will be able to identify, by peculiarities of their flight, many birds that are too far away for identification in any other manner. The Turkey Vulture, soaring with slightly raised wings and frequently tipping from side to side, can be distinguished readily from an eagle, which soars on a level course with horizontal wings. The Black Vulture soars more like an eagle. The Wood Ibis, which flies with a series of flaps, followed by a glide, can be distinguished from a Sandhill Crane, which flies with more regularly spaced wingbeats. The Sandhill Crane and Ward's Heron might be confused when on the ground, but in flight the crane's outstretched neck and short, fast wingbeat easily distinguish it from the heron, with its retracted neck and slow, deep wingbeat.

The flight of the Chimney Swift has puzzled many observers. At times the swift seems to beat its wings alternately, at other times simultaneously. In the accompanying pictures (Figs. 61–68) the lower bird is beating both wings together. The upper bird is using different timing. Both its wings seem to start the beat together, but one moves faster during the stroke. The swift has little tail area for steering. In these pictures its body seems to change direction slightly in response to the faster beat of one wing—an extreme example of the technique by which many birds steer partly by the use of the wings.



These pictures, taken at 64 frames* a second, are not quite fast enough to make a clear picture when the wing is making the stroke, but are fairly clear at the beginning and end of the stroke. Thus, blurred or sharp, they tell the story.

BALANCE AND CONTROL

Bird and plane steer and balance in much the same manner, but the bird has the more efficient and versatile equipment for these purposes. Both plane and bird can roll to one side or stay on an even keel by increasing the lift of one wing and decreasing the lift of the other. To do so the plane uses ailerons, made by cutting out a section of the trailing edge of each wing and putting it on hinges. The pilot can increase or decrease lift by raising or lowering the aileron, thus increasing or decreasing the angle of attack for that part of the wing.

The flying bird needs no ailerons. It needs only to beat one wing a little faster than the other or to change its angle of attack slightly in order to increase lift on one side. When the bird is gliding, however, it may use the outer part of the wing as an aileron, rotating it to change the angle of attack.

The plane has a tail to steer upward or downward. A horizontal stabilizer at the end of the tail functions much as an extra wing does to help lift the weight of the tail. At the trailing edge of the stabilizer there is an elevator, fastened by hinges, which can be turned up or down to increase or decrease lift, just as the ailerons do for the wings. Up from the middle of the stabilizer stands a rigid, vertical fin, which helps to keep the tail from swinging sideways and also helps to keep the plane from tipping or rolling. At the rear

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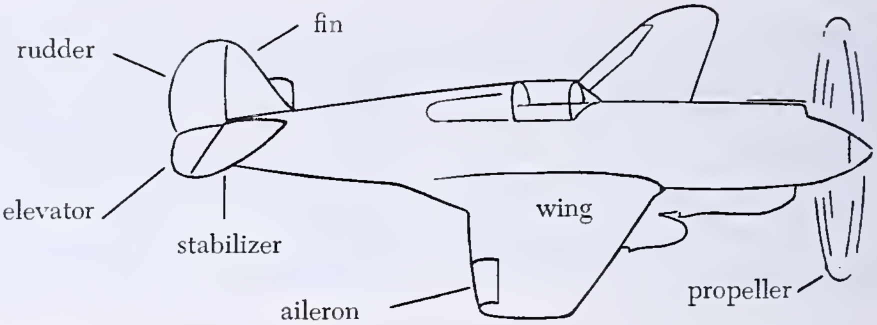
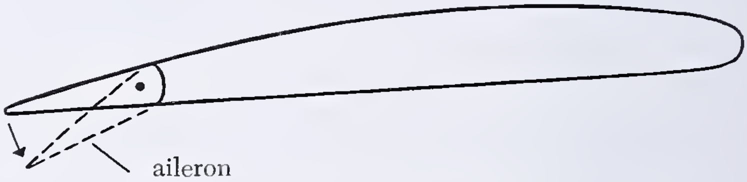
* The word "frames" refers to the timing of motion pictures which are normally taken at 16 exposures (frames) per second. The greater number of pictures made for this study were taken at 128 frames per second.



69. Steering and balancing equipment of a plane.



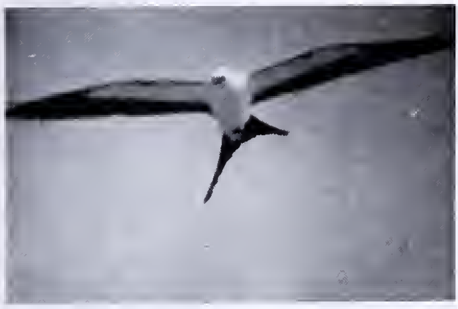
70. Cross section of the wing of a plane, showing how the ailerons turn down to increase angle of attack and lift.

edge of this fin there is a rudder, fastened by hinges. Like an aileron, the rudder gives the necessary lift or push to either side for steering the plane. (See Figures 69 and 70.)

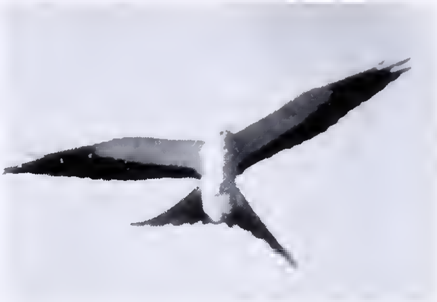
The bird, with a propeller on the end of each wing, needs only to beat one wing a little harder to drive one side forward, just as an oarsman pulls harder on one oar to steer his boat. The bird can twist its tail to steer to either side or up or down. Moreover, by spreading its tail it can supplement the lifting area of its wings.

The tail of the bird, indeed, has many uses. It can steer in any direction, act as a brake, form a slot behind the wings, or become a part of the bird's lifting surface, supplementing the wings. The tail feathers overlap; starting from either side the next inner feather overlaps the outer one.

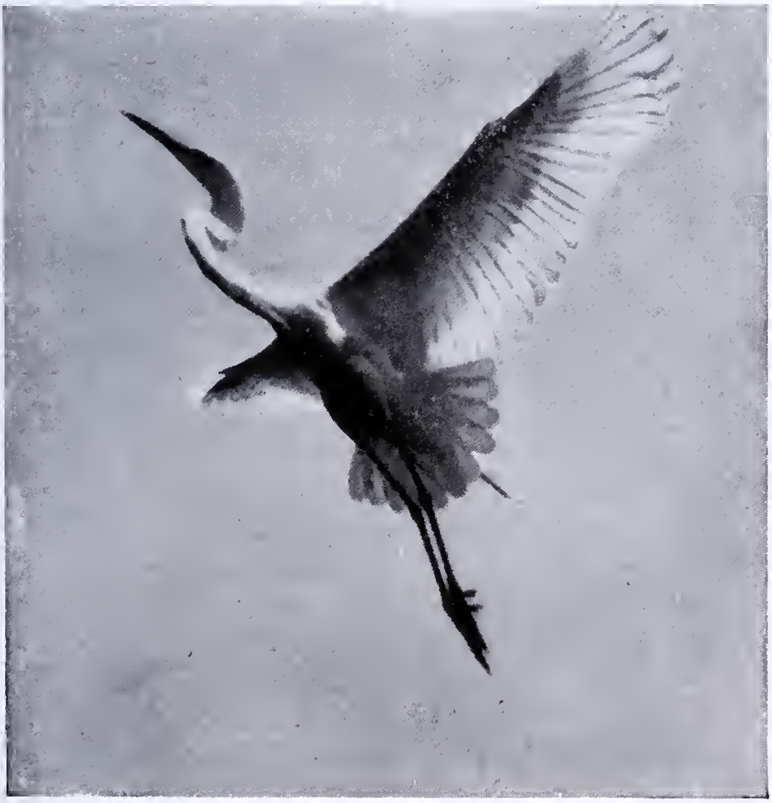
The Swallow-tailed Kite (Fig. 71) twists its tail to steer. It may turn its tail so that either the upper or the lower surface will strike the air stream in steering. The two sides of the tail may be controlled separately, as shown in Figure 72, where the bird's right outer tail feather is being moved fast enough to bend it against the air. Flying very slowly, the egret shown in Figure 73 spreads its tail



71. The Swallow-tailed Kite twists its tail to steer.



72. The two sides of the tail may be controlled separately.



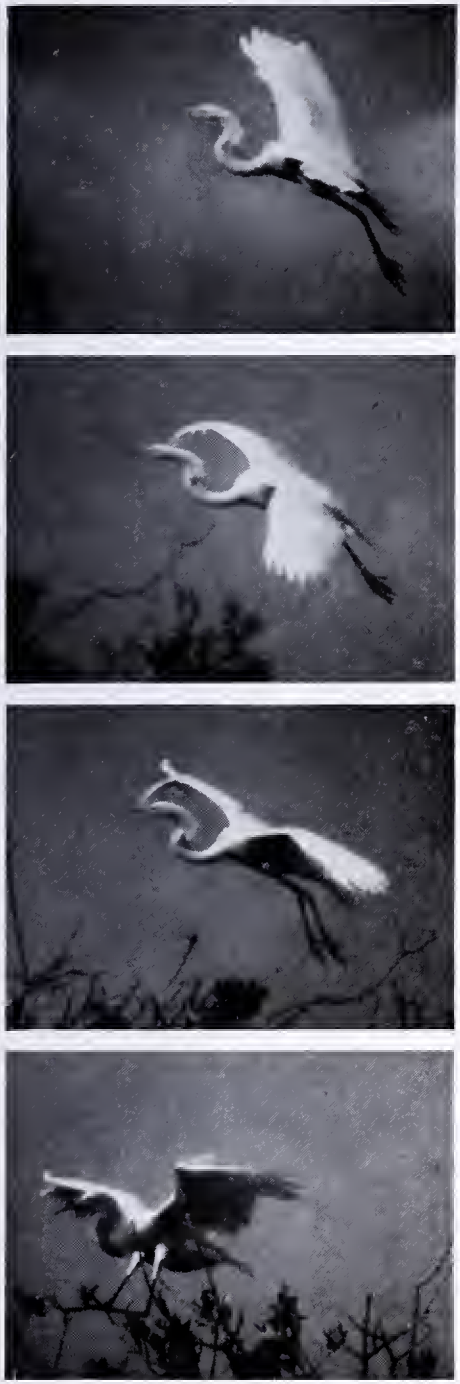
73. The tail is spread wide in slow flying, to increase lifting area.

Photograph of an American Egret by Hugo Schroder.

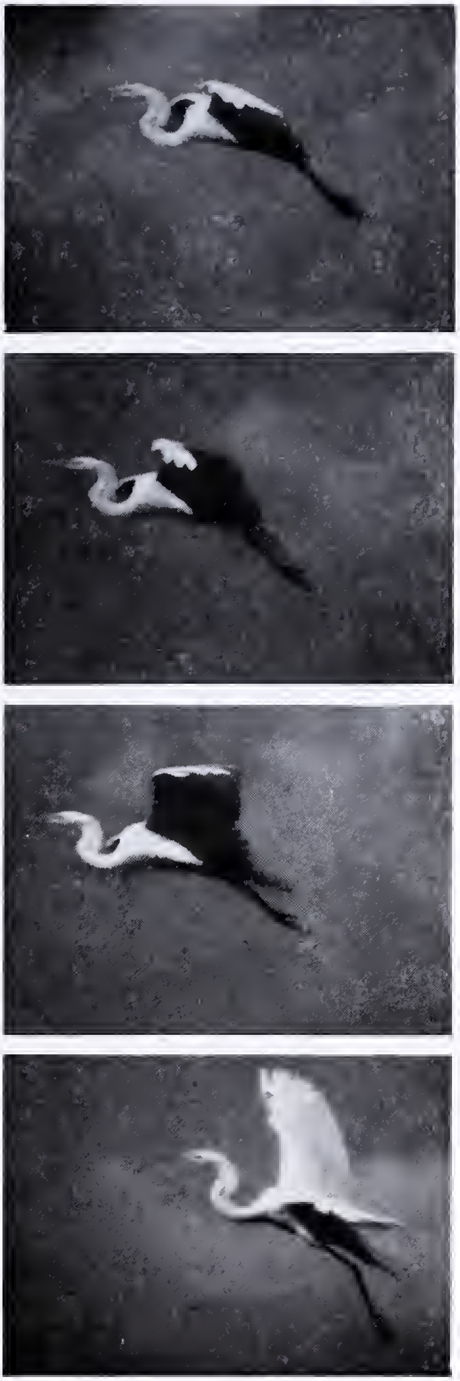
wide to increase lifting area. The wings are held forward to balance the added lift of the tail, and the alula slots are open.

Balance and control in a gusty wind are illustrated in Figures 74 to 81. Gliding in to a landing with nearly motionless wings, this American Egret gives a beautiful demonstration of its equipment for balancing and steering. In Figure 74 the uptwisted tip of the front left primary, a small dark wedge-shape at the front of the wing tip, is in a typical position of a primary tip during a glide, giving just enough lift to control equilibrium. In the next picture (Fig. 75) the four outer primaries, controlled separately by the finger joint, increase their angle of attack, like an aileron. Thus the lift and drag of the wing are increased. But the wing has been pulled back and lifted too much, and its angle is now flattened to restore balance (Fig. 76). In the following picture the wing tip and the alula have been turned downward to brake and depress the wing. Now the right wing has risen too far (Fig. 77). The right wing now starts to turn down (Fig. 78). The outer primary, controlled separately by the finger tip joint, turns first and appears to make a slot that speeds the air flow under the wing, to reduce its lift. Both wing tips then turn down (Fig. 79) to reduce lift before landing. The left wing, turned down steeply, appears to be acting as a brake. The bird is swung around (Fig. 80) by the braking action of the left wing. Now the right alula rises and the right tip turns down to brake and check the swing. In the last picture (Fig. 81) the bird has dropped considerably. Its progress may be measured by the forked stick in the background. The feet are thrown forward to feel for a landing branch. Both alulas have risen. The angle of the wings has increased to maintain lift as speed is reduced.

Controls in action are illustrated in the next series of photographs (Figs. 82–88). In the first photograph (Fig. 82) the American Egret, gliding to a landing in a strong wind, has evidently been hit by a gust from its left (right side of picture). It lets its left wing go slack to rise with the wind and ease the rolling force. Then the bird's left wing rises more (Fig. 83), its right wing increases its angle against the air while moving forward and downward and gives enough lift to bend its tip up and check the roll from the gust. Progress may be measured by the distance from the neck of the Brown Pelican below. In the third picture (Fig. 84) the bird's whole right wing has increased its angle against the air, to help lift. Its left wing,

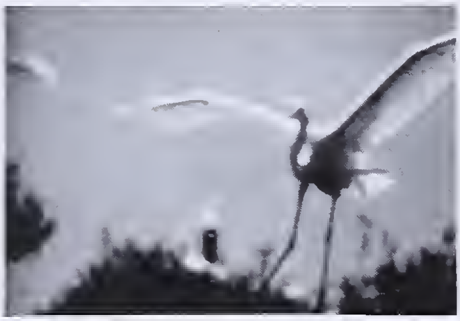


74 – 77

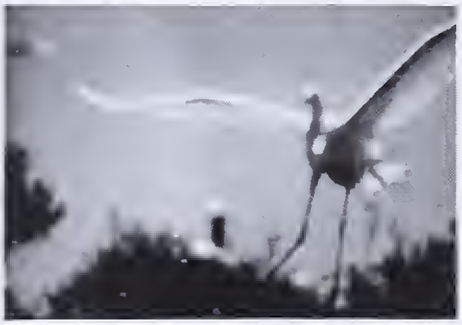


78 – 81

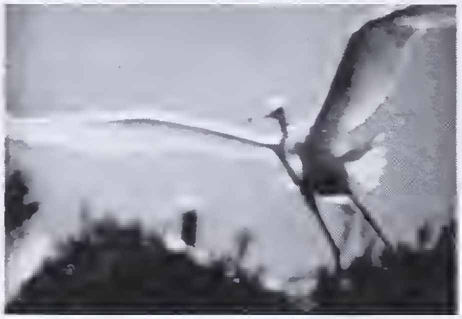
Balance and control in a gusty wind are demonstrated in the landing of an American Egret.



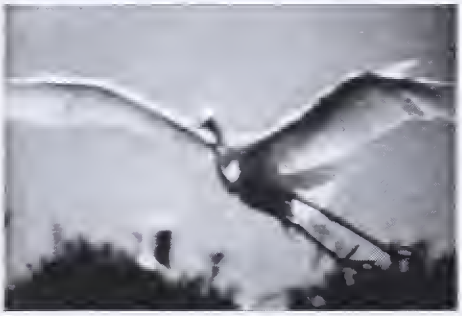
82.



83. 1/40 second (3 frames) later.

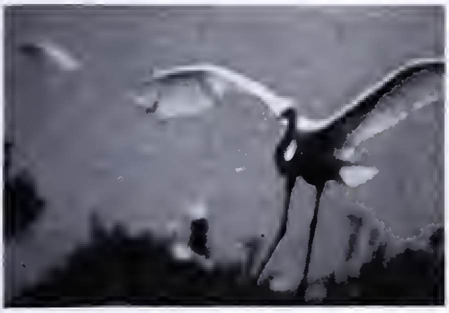


84. 1/6 second (20 frames) later.

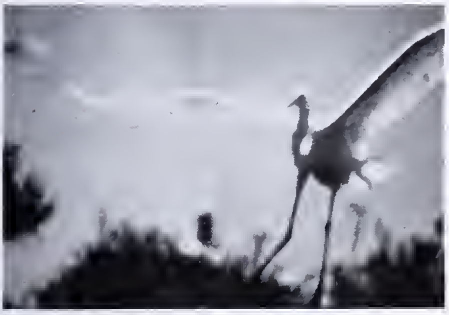


85. 1/13 second (10 frames) later.

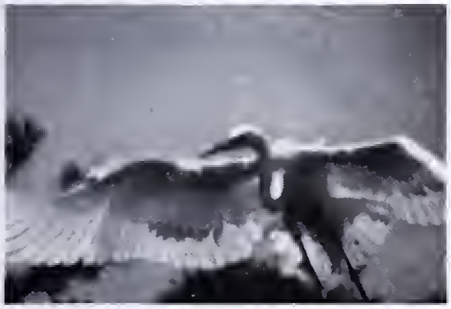
An American Egret, gliding to a landing in a strong wind, shows controls in action.



86. 1/4 second (32 frames) later.



87. 1/6 second (21 frames) later.



88. 1/11 second (11 frames) later

still slack, has risen higher and is striking the air at almost a 90-degree angle. The left alula is rising and the tail has swung to its left, both probably acting as brakes to counterbalance the drag of the extended right wing. The legs swing out to counterbalance the rolling force of the gust. Before the development of ailerons, this same technique was used by some of the early experimenters with gliders.

Everything is under control in the next picture (Fig. 85). The left wing drops again, its alula raised so high that it appears to be acting as a brake. The right wing has risen slightly, in preparation for giving more lift, but is not lifting yet, as the flat, unbent tip feathers prove. The egret then rises perceptibly (Fig. 86), measuring again from the neck of the pelican, and is now in position to coast in to its landing branch. The right alula has risen to prevent stalling, while the wing drops back for a half stroke to maintain lift and altitude during the glide.

The wings then start forward on a half stroke, nearly horizontal, to maintain lift (Fig. 87). Their increased velocity against the air permits a lowering of the alulas and a lower angle of attack. The tail, spread wide and turned down, acts like a flap, with slots between itself and the wings.

In the last picture of the series (Fig. 88) the angles of wing and tail have increased steeply to brake speed, and the wing tip is bent back.

DEVICES FOR THE TAKE-OFF

A bird has two chief problems in take-off. It must first attain enough forward speed to lift it in the shortest possible time; it must next get some aid for its lift before gaining the speed for normal flight.

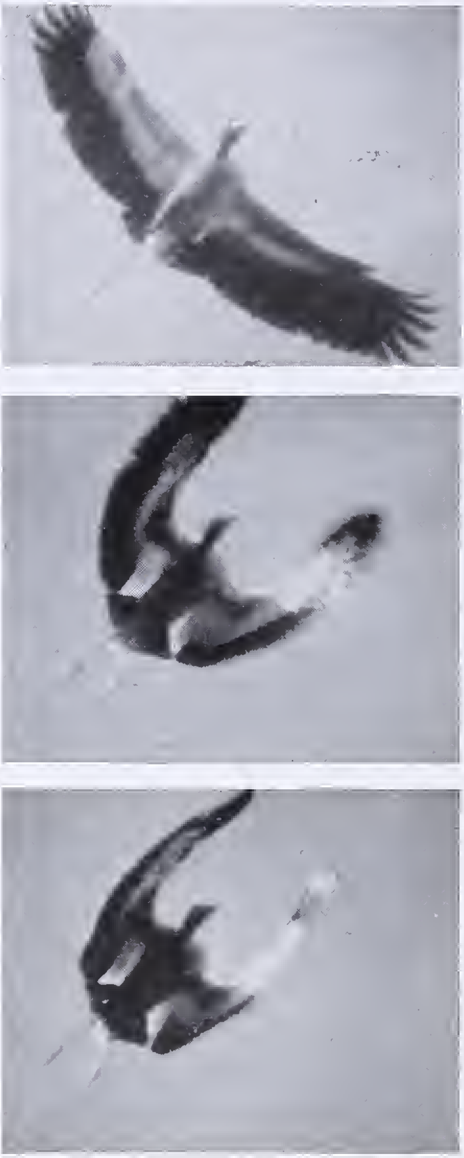
Birds solve the problems of take-off in several ways. The long-legged heron gets a big boost with its first leap into the air. The coot and the swan take long runs on water before they gain enough speed to rise. The Gannet, with its long narrow wings and short legs, can rise from the top of a wave, into a good breeze, but is almost helpless on land, where it lives on the edge of a cliff, from which it launches itself into the air and glides downward until flying speed is attained.

The Frigate-bird, a superb glider, is helpless on land. South American Condors are caught by enticing them with bait to land in an enclosure where there is not room for the necessary take-off run, and there they must stay.

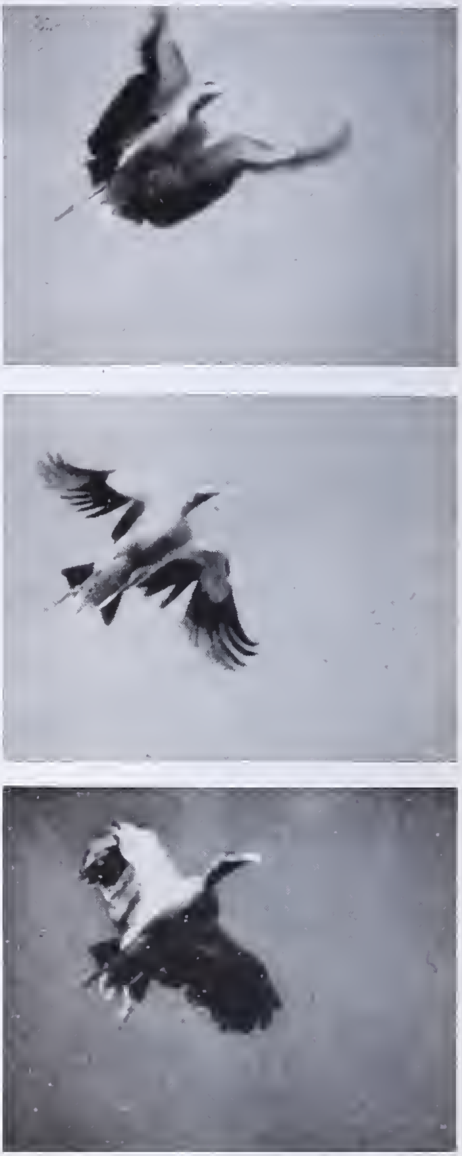
Two of the most interesting take-off devices are the helicopter and the variable propeller. Both are used, with modifications, by many birds. The take-offs by Wood Ibis, American Egret, and Canada Geese, shown in the accompanying photographs (Figs. 89–110), illustrate the use of these devices.

The Wood Ibis becomes a helicopter to achieve a fast rise (Figs. 89–94). The wings sweep forward and back nearly horizontally, producing a climb that takes more power than forward flight requires. The Wood Ibis gets this extra power by shortening the wing motions, breaking the stroke into several stages, and moving one joint at a time to give the muscles better leverage. The wings first sweep forward horizontally from the elbows, the alulas and tip slots open (Fig. 89). Toward the end of the forward stroke (Fig. 90) the outer wing is twisted to make a propeller blade, with the power directed upward. The position of the arm bones, silhouetted through the wing, shows that the upper arm, from shoulder to elbow, has scarcely moved. The motion has come from the elbow. The elbows then swing downward (Fig. 91), approaching each other below the bird's body. The outer wings, while they point forward, are vertical, edgewise, like an extended hand, with thumb up and back edge down. Now the elbows will swing back past the hips, then rise above the body to the position shown in the next picture (Fig. 92). Here the elbows have risen above the back, while the outer wings are snapping backward from the wrist. The pressure against the air bends and twists the outer wing. The primary feathers are twisted into propellers with their power directed upward. Their upper surface now faces downward, in the opposite direction from the twist in forward flight.

The end of the back stroke, with the elbows raised above the back, is shown in the next photograph (Fig. 93). The feather tips are still bent forward by the pressure of the air. The start of the next forward stroke follows (Fig. 94). The wings have straightened, and now the power of their forward drive twists and bends the feathers backward in a position just the opposite of the bend and twists at the end of the back stroke, 1/41 second earlier. Diagrams of the primary



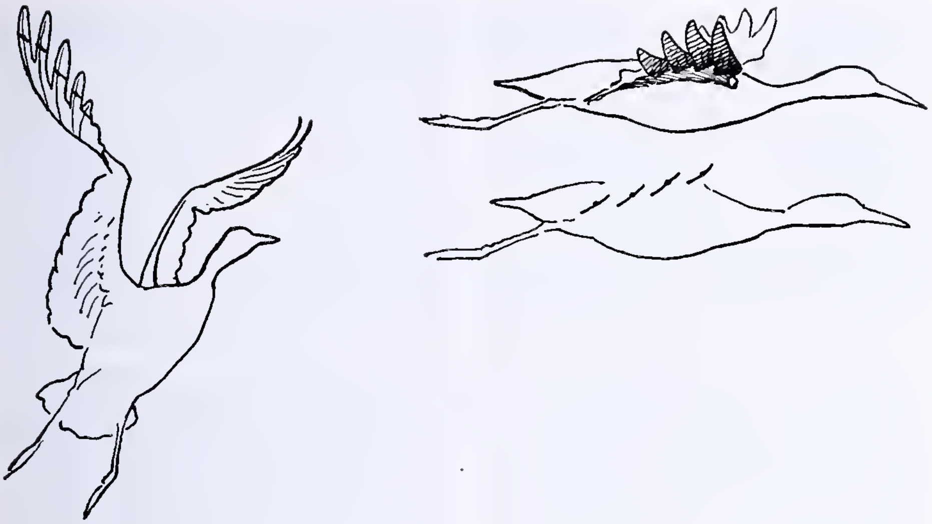
89 – 91



92 – 94

A Wood Ibis becomes a helicopter to achieve a fast rise.

In sequence, top to bottom, left column first: Fig. 89,—the wings sweep forward; 90,—1/13 second (10 frames) later; 91,—1/64 second (2 frames) later; 92,—1/26 second (5 frames) later; 93,—1/21 second (6 frames) later; 94,—1/41 second (3 frames) later.

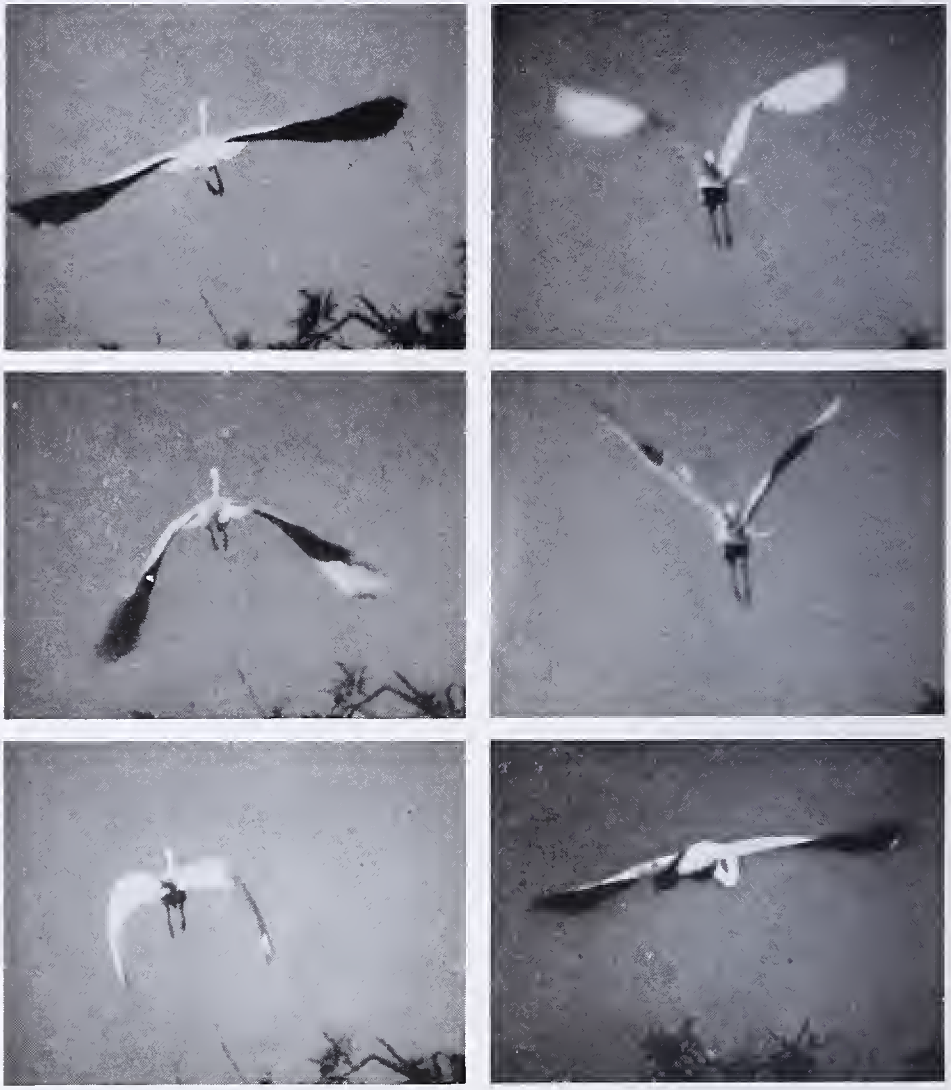


95 and 96. Diagrams of the positions of primary feathers during back stroke, as illustrated in Figure 92, and forward stroke, as illustrated in Figure 90. Note that the angle of the primaries in Figure 96 is the exact opposite of their angle in a forward stroke. Here they are supplying lift instead of forward drive.

feathers in the positions assumed during the back stroke (Fig. 92) and the forward stroke (Fig. 90) are shown in Figures 95 and 96.

In the next series of photographs (Figs. 97–102) an American Egret is shown in a catapult take-off, helped by a variable propeller. The bird's long legs project it into the air, giving it enough lift for a start (Fig. 97). The wings concentrate on forward speed. With wings beating fast, the pressure against the air twists most of their surface into propellers, leaving little surface to supply lift. The tail, spread wide, helps by acting as a flap and making a slot behind each wing to add lift till the bird gains speed. The propellers appear more than twice as big as in normal flight. Now the inner and outer halves of the wings work with different timing (Fig. 98). The inner wings end their down stroke and will now start upward, still at an angle to give lift. The propellers continue on the down stroke. In the next photograph (Fig. 99) the outer wings have just finished the down stroke, while the inner wings have risen halfway on the up stroke; the angle of the inner wings shows that they are still supplying lift.

In the next photograph (Fig. 100), the inner wings have reached the top of their stroke and then wait for a split second while the



97 – 99 100 – 102

An American Egret makes use of a catapult take-off, helped by the variable propeller.

In sequence, top to bottom, left column first: Figure 97,—the bird's long legs catapult it into the air; 98,—1/18 second (7 frames) later; 99,—1/18 second later, inner and outer sections of wings work with different timing; 100,—1/14 second (9 frames) later; 101,—1/41 second (3 frames) later; 102,—position similar to that in first picture (Fig. 97), but after bird has picked up more speed.

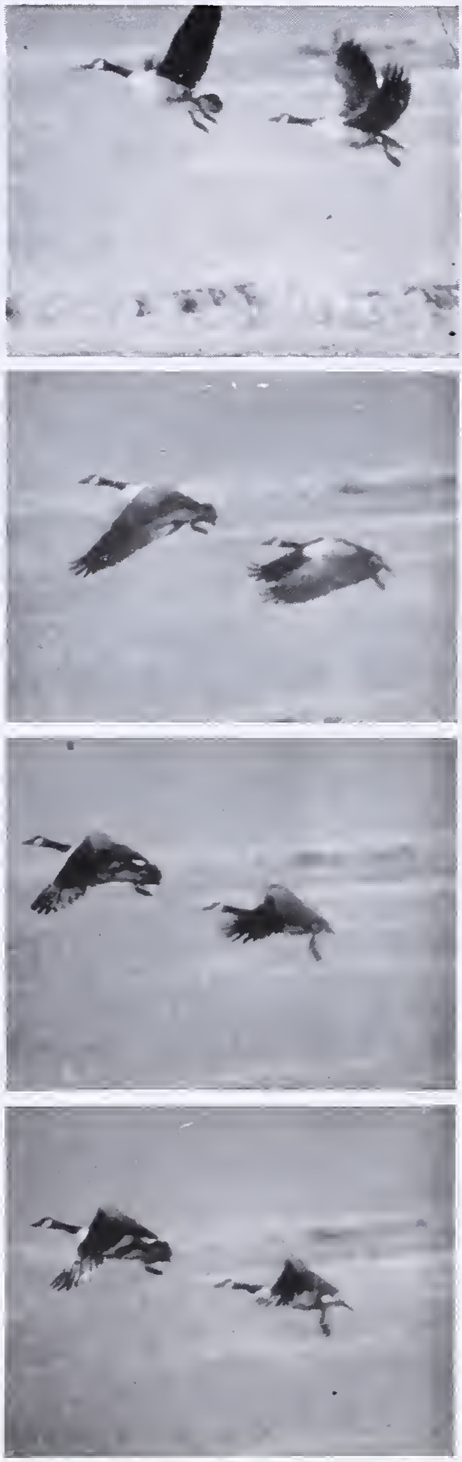
outer wings rise. Their downtwisted back edges show that they are still acting as propellers as they sweep upward and backward against the air. The top of the up stroke is reached 1/41 second later (Fig. 101). The upward bent feathers at the midpoint of the wings show that this area of the wings has already started downward, whereas the white upper surface of the right wing tip is still twisted slightly downward, showing that it is moving upward against the air. In 1/10 second more the wings will be back in the first position (Fig. 97). Thus about 3/10 second is required for the full up-and-down stroke.

Figure 102 shows an American Egret in a position comparable to that shown in Figure 97, but after it has picked up more speed. Less effort is required; the wings exert less pressure against the air, their twist is reduced and the propellers become smaller. When normal speed is attained they will be even smaller.

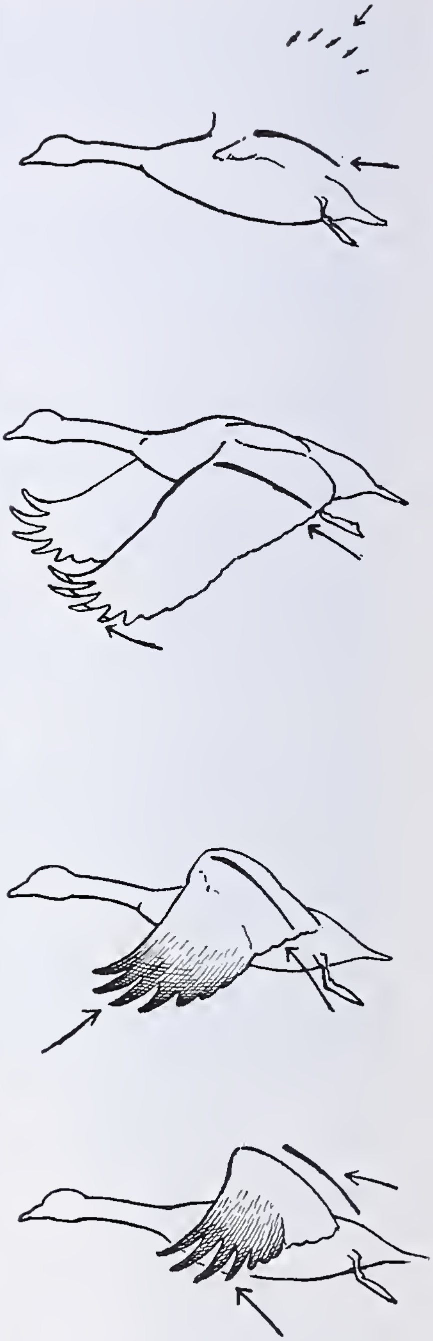
In the next series (Figs. 103–110) some finer points of a take-off are demonstrated by Canada Geese. On the rear bird in the first picture (Fig. 103), which is partly through the down stroke, the air pressure has bent the primary feathers (the propellers) forward, driving the wing forward with them. In the next picture (Fig. 105), the wing tips have swept forward a full body length and have thus attained enough forward speed to give good lift. The angle of the primary feathers has changed. During this part of the stroke they cannot supply forward drive, but their upcurved tips show that they are giving lift. In the next picture (Fig. 107) the bird is partly through the back stroke. The inner wings are still giving lift, and their angles have increased to compensate for their reduced speed against the air as they move backward. The forward curves of the primary feathers show that they are giving both lift and forward drive. Halfway through the back stroke (Fig. 109), the forward bending primary feathers are giving strong forward drive. The bird's progress forward and upward can be measured against the bushes in the background.

LANDING

Under most conditions landing is a more complicated and exacting feat than taking off. The bird must so gauge its speed as to land on the selected branch or opening with the least possible momentum. It must use its wings, not always at the most efficient



103, 105, 107, 109



104, 106, 108, 110

103 and 104. Down stroke, showing angles of primary feathers driving; angle of inner section of wing, lifting.

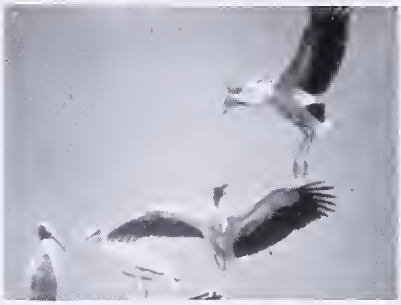
105 and 106. End of forward stroke, showing angles of primary feathers, lifting; angle of inner section of wing, lifting.

107 and 108. Start of back stroke, showing outer section of wing moving backward, tips of primaries supplying lift; inner wing, moving forward with the bird, supplying lift.

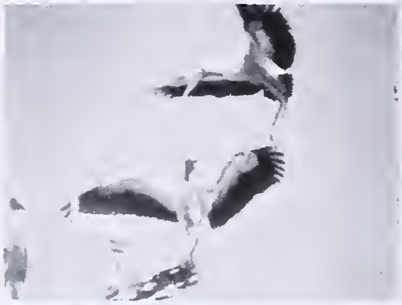
109 and 110. Middle of back stroke, showing inner section of wing still moving forward with the bird, supplying lift; outer section of wing sweeping backward against the air, supplying forward drive.

Canada Geese demonstrate some finer points of the take-off.

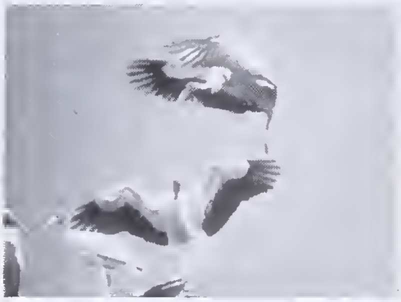
The sketches show the position of the inner and outer sections of the wing in the forward and back strokes of the take-off.



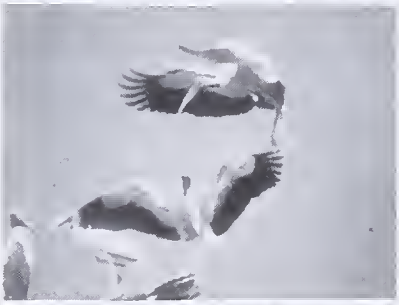
111. The bird hovers motionless, looking for a spot to land.



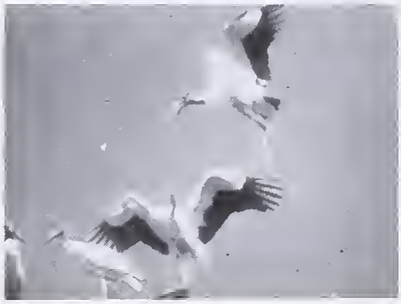
112. 1/21 second (6 frames) later.



113. 1/26 second (5 frames) later.

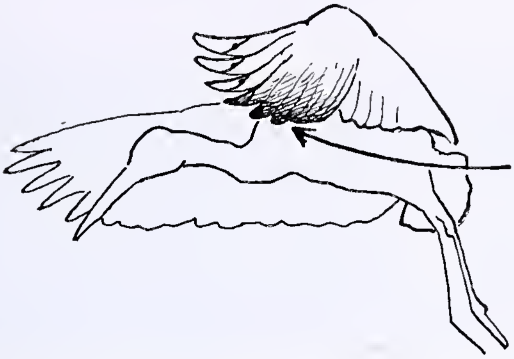


114. 1/42 second (3 frames) later. Start of the back stroke.



115. 1/26 second later. Near end of the back stroke.

A Wood Ibis demonstrates a perfect helicopter landing.

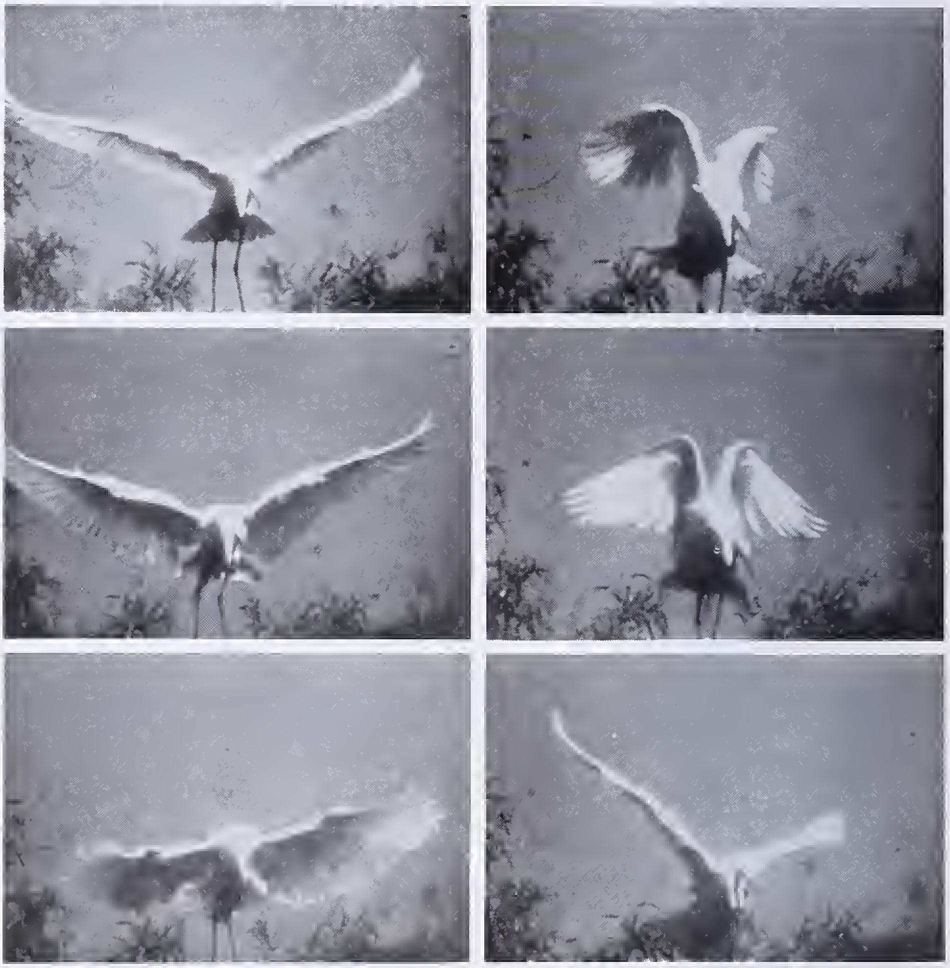


116. Position of the outer and inner primaries on the back stroke (see also Figs. 108 and 110). Their angles show that they are supplying some lift.

angle or position, but often in a position dictated by some interposing branch.

The greatest skill is required for such water birds as the herons or Wood Ibis to set their long legs down without damage in a tangle of branches. In these birds, some of the clumsiest appearing on land, we see some of the best examples of expert landing technique.

A perfect helicopter landing is demonstrated by the Wood Ibis (Figs. 111–115). The bird first hovers (Fig. 111), looking for a spot to land. Then the wings sweep forward without dropping below the shoulder (Fig. 112). At the end of the horizontal forward stroke, the upcurved primaries are still giving lift. At the start of the back stroke (Fig. 114), the outer primaries are twisted, the inner primaries are bent inward by the pressure against the air, and all supply some lift as they sweep backward. Near the end of the back stroke (Fig. 115) the inner wing, out as far as the wrist, has hardly moved from the position shown in Figure 114. Rather, the motion has been from the wrist outward. The upward curves of the primary feathers show that they are still giving lift. Now the elbows and wrists will straighten, throwing the wing tips outward (still giving lift), to reach the first position (Fig. 111) again in 1/9 second. On the forward stroke the tail snapped down from its position in Figure 111 to that in the fourth picture (Fig. 114), thus helping to lift the rear end of the bird as the lift of the wings was moving forward. When the wings move backward, the tail again rises to the first position. Throughout the entire wing beat the position of the bird, measured from the tip of the stump to its neck, has not moved perceptibly. The thighs rose slightly from the first to the third photograph, but



117 – 119

120 – 122

An American Egret uses the reversed propeller
and other landing aids.

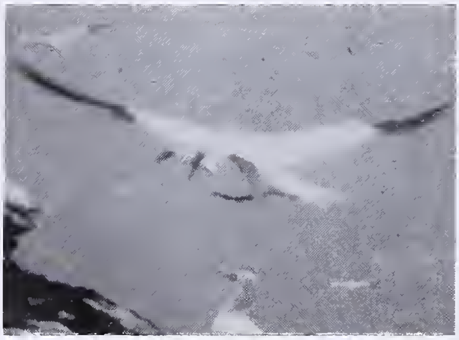
In sequence, top to bottom, left column first: 117,–coasting to a landing in a tangle of branches; 118,–the ruffled feathers show that stalling has begun; 119,–the propellers have gone into reverse; 120,–end of the forward stroke; 121,–the bird settles toward a landing; 122,–wings in position to start next forward stroke.

in the fifth (Fig. 115) they are back in their first position again. The sketch (Fig. 116) shows the position of outer and inner primaries on the back stroke.

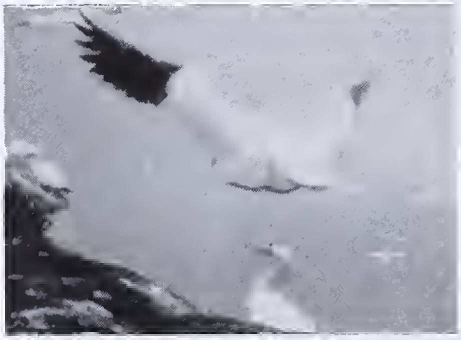
The American Egret in the next series of photographs (Figs.117–122) is making use of the reversed propeller principle and other landing aids. Coasting in to a landing among a tangle of branches, the bird must make a quick stop under perfect control to avoid breaking a leg or a feather. The ruffled feathers on the bird's right wing (left of picture, Fig. 117) show that it has begun to stall. The outer primaries (Fig. 118) are rotated slightly, their rear edge downward, while the air pressure bends the tips upward, preparatory to going into reverse. The rear half of each wing is turned downward, apparently by the membrane that controls the secondary feathers, without any apparent rotation of the wing bones. This gives the effect of a down-turned flap on a plane's wing and also makes a slot above each side of the tail. The ruffled feathers at the front edges of the wings show that the wings are stalling. The alulas have risen.

The wings sweep forward (Fig. 119) so that the upward bent tips of the primary feathers strike the air at an angle to exert backward pressure. The propellers have now gone into reverse. With the forward sweep and increased velocity of the wings, the air flow over them smooths out and the feathers lie flat again. Lift is restored. In the preceding picture (Fig. 118), the shadow under the wing shows the silhouette of the covert feathers lying flat against the secondaries. In Figure 119 the shadow has moved far back under the wing, showing the covert feathers are raised to give the effect of a split flap and a slot through the wings. At the end of the forward stroke the left wing is striking flat against the air, stopping the bird. So far the bird has maintained a level glide, as may be seen by comparing the level of the heels (the lumps in the legs) with the leaves near by. The outer wings then beat downward and backward (Fig. 120), supplying some lift as the bird settles toward a landing. The heels have dropped several inches since the preceding picture (Fig. 121). The membrane folded over the wrist gives one a means of judging how much of the wing is composed of this substance. In the last photograph (Fig. 122) the wings are back in position to start the next forward stroke.

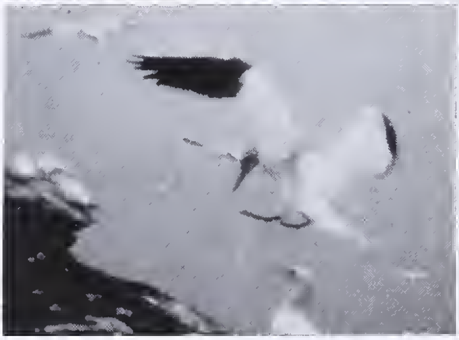
In another series (Figs. 123–131) the Gannet and the Osprey are shown alighting. The Gannet can land against the face of a



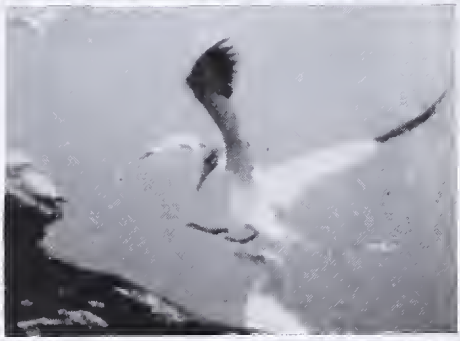
123. The Gannet begins to settle down.



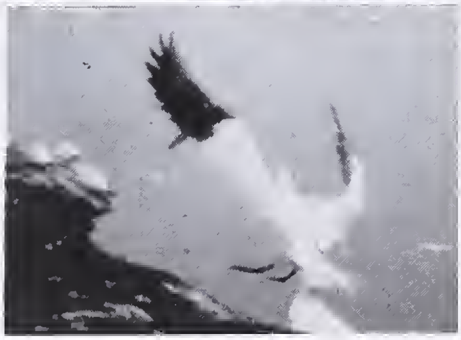
124. 6 frames later.



125. 5 frames later.

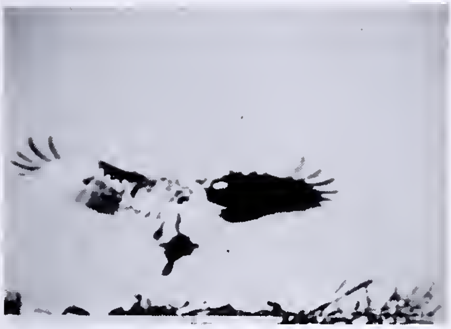


126. 10 frames later.

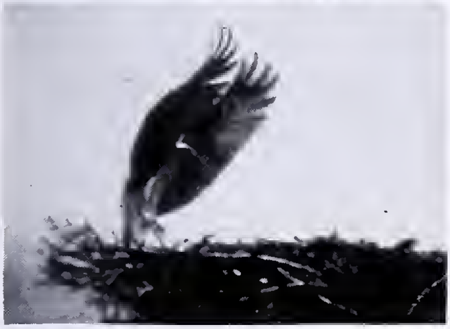


127. 9 frames later.

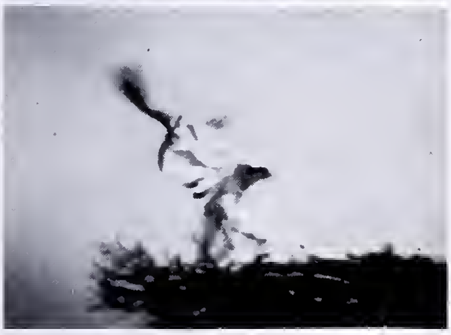
The landing of a Gannet



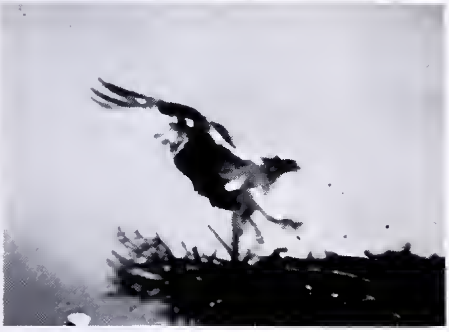
128. The Osprey may come in with propellers reversing.



129. Or it may make a parachute of its wings to land.



130. 8 frames later.



131. 4 frames later.

The landing of an Osprey.

The wings supply lift, as they beat backward.

132. White Pelicans soaring, spaced along the periphery of a thermal. Two birds may be seen at a higher level than the group.

steep cliff without marring a feather; where the face is not too steep and the bird has room it will settle down with minimum wing motion. The wings rock forward and back, alternately braking and lifting.

The Osprey may come in with propellers reversing (Fig. 128), or it may sweep the wings upward at the end of the forward stroke to form a parachute (Fig. 129), then snap them backward from the wrist, using a sort of overhand stroke to press downward against the air—a very different back stroke from any other we have seen (Figs. 130–131).

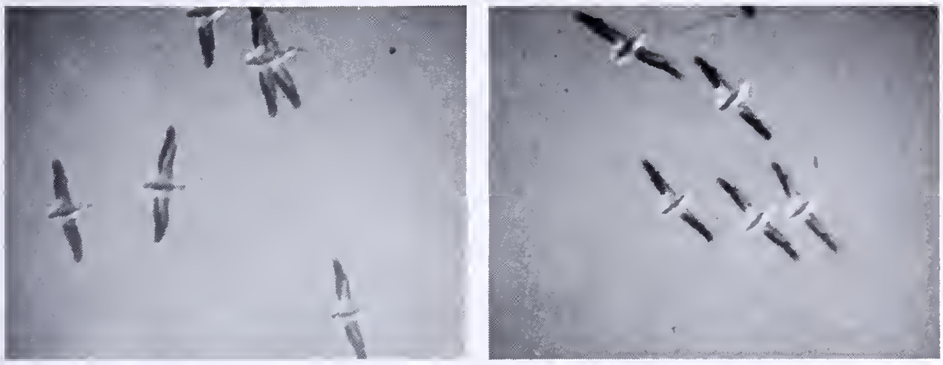
SOARING AND GLIDING

Of all the bird's powers in the air, probably none has aroused more interest and speculation than the ability to soar. To rise in the air on motionless wings and disappear from sight seems almost like magic.

We know the answer now, but even so it is difficult to realize as we watch a bird soar, that actually it is coasting downhill on a rising current of air. The speed of its rise is the difference between the rate at which the air is rising and the speed at which the bird is sinking or gliding downward. The only known exception is dynamic soaring, as for instance, where the bird has gained momentum horizontally from one air current and then moved into another air current of different velocity or direction.

AIR CURRENTS

We know something about the air currents that enable a bird to soar. When the wind strikes some obstruction—a sail, the shore



133 and 134. White Pelicans following the outline of a thermal. In Figure 134, 174 frames later than Figure 133, the birds have turned considerably. Even during these soaring evolutions, when it must be difficult to stay "in formation," the birds apparently try to ride one another's wing-tip vortexes.

line, or a mountain side—it rises over the obstruction. A bird can soar on this rising obstruction-current. The heavy, cold air of an advancing cold front pushes the warmer air upward. Birds can sometimes soar on this rising air. Some types of land absorb more heat from the sun than others. A bare field, for example, or a patch of sand warmed by the sun will heat the air over it more quickly than will water or a forest. This light, heated air rises, and a bird can soar on the rising current.

This rising current, or "thermal," may be in the form of a huge bubble, or it may be a solid column. The shapes and sizes of air currents vary with wind and temperature. Sometimes the outlines of a current may be ascertained by watching while soaring birds follow it (Figs. 132–135). An eagle or vulture soaring up in great circles is spiraling within the boundaries of a rising air current.

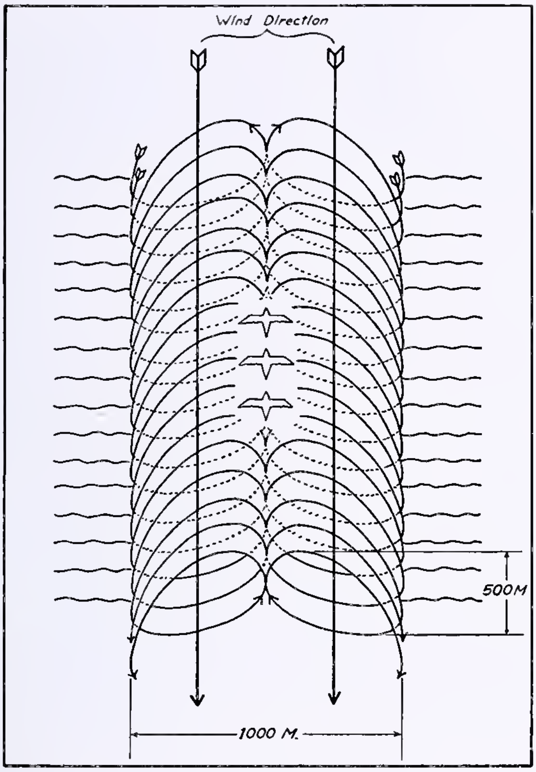
Birds soaring over the ocean follow a different pattern, and a very interesting one. Here there are no obstructions higher than the waves. But the obstruction currents caused by them furnish free rides for many birds, ranging in size from the petrel to the albatross. The ocean surface is too nearly uniform in temperature to cause the type of thermal current that often makes soaring possible over land. But under certain conditions birds can soar to great heights and for tremendous distances over water. Some birds, such as the Herring Gull, are weak fliers and they avoid long flights as much as possible. They are dependent on rising currents for long

135. A group of Wood Ibis soaring along the periphery of a thermal.

distance travel. From watching these birds on their ocean travels much has been learned about air currents over the ocean.

An interesting study was made by Alfred H. Woodcock (1940) in the vicinity of Cape Cod. It seems to bear out the results of laboratory experiments (Graham, 1934) made in England in which smoke was used to show the outlines of different types of convection currents over a surface with a steady and uniform source of heat. The size and pattern of these currents varied widely with temperature differences, with the height of the layer in which the current was formed, and with the rate at which the air was moving.

Photographs of these experimental smoke patterns show the air rising, not in bubbles, as many thermal currents over land surfaces do, but in a closely packed series of vertical hexagonal columns or cells, much like the cells of a honeycomb. Under some conditions the air in these cells moves up in the center and down around the edges; at other times down in the center and up around the edges. As the rate of air flow over the heated surface is increased—corresponding to an increase in the wind over the ocean—these cells begin to tilt in the direction of the wind; until finally they lie flat and ro-

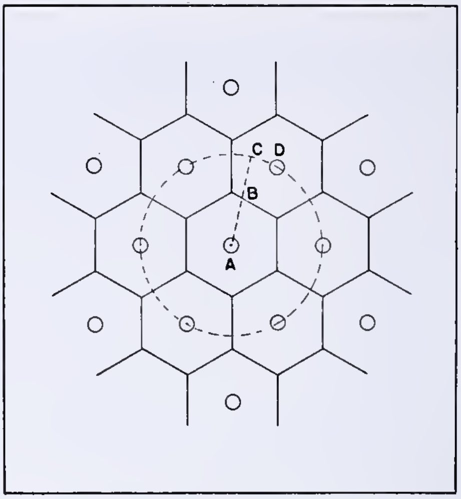


136. Pattern of air currents by which birds can soar over the ocean in a straight line with winds from 15.5 to 28 miles per hour. ("Longitudinal roll convection cell diagrammatically idealized, showing approximately the proportion of depth to width. The relative magnitude of the helical motion in the direction of the wind is foreshortened for convenience in presentation.") After Woodcock, 1942.

Courtesy *Scientific Monthly*.

tate about their axes. Each cell rotates in the direction opposite to that of its neighbor, the one clockwise, the next counterclockwise. Thus their adjoining sides move in the same direction. (See Figures 136 and 137.)

Woodcock's studies of soaring gulls, including observations extending for many miles offshore, indicated patterns of air flow with interesting similiarity to these experimental patterns. During the summer, when the air over the ocean is warmer than the water, no gulls were seen soaring off the New England coast except in obstruction currents over a ship. In the fall, however, when the air was colder than the water, soaring started, beginning when the



137. Steady-state hexagonal convection cells in the approximate pattern (horizontal section) of air currents over the ocean with wind from 1.1 to 15.5 miles per hour. Under such conditions the birds soar in circles. Each hexagonal cell of the honeycomb pattern is a column of air rising in the center and falling around the edges, or sometimes vice versa. Gulls can soar around these rising columns of air and glide from one to another. After Woodcock, 1942.

Courtesy *Scientific Monthly*.

air temperature became 2°C. colder than the water, and when there was a wind velocity of at least half a meter per second (about 1.1 m.p.h.). Until the wind reached a velocity of 7 meters per second (about 15 1/2 m.p.h.), the soaring was always in circles. Then, provided the air was cold enough, the pattern would change. When the air was more than 4°C. colder than the water, and the wind over 15 1/2 m.p.h., most of the gulls began to soar in straight lines, though some still circled. As the wind increased to about 19 m.p.h., the circle soaring decreased. It stopped entirely when the wind reached about 24 m.p.h., and soaring became wholly linear, indicating that air pattern had changed from columnar cells to linear "strip" cells. With wind at a little over 28 m.p.h., soaring ceased, indicating a breaking up of the air pattern.

By comparing the positions of individual gulls soaring in the same air column, but at different heights, it was possible to estimate the size, shape, and direction of the column. At low wind speeds the rising air columns were nearly vertical and continuous—not merely rising air bubbles. As the wind increased, the columns began to tilt in a down-wind direction. At wind velocities between 15 1/2 and 28 m.p.h., strip cells developed.

The soaring gulls indicated that both types of cell start within 100 to 300 feet of the ocean level and extend upward to considerable heights. Gull altitudes were measured with a range finder up to 2000 feet, but birds were seen at much higher altitudes. With wind velocities as high as 28 m.p.h., gulls would soar past the ship to windward on motionless wings, gaining altitude, and disappearing in a few minutes.

Woodcock (1940, pp. 221, 223) described two experiences which are relevant here and may be quoted.

> Even during mid-winter off our coast, there are times when warm air masses coming from the southwest practically 'ground' the Herring Gulls until colder air moves in. During the 'Atlantis' cruise to Bermuda, January 4 to 11, 1939, there were two such periods. On January 5, we were in a high-pressure area, and the air was six degrees Centigrade colder than the water. The gulls were in the air soaring during the whole of the day. The evening of the 5th, a warm front passed us, bringing in a mass of air which was warmer than the surface water. This warm air remained with us on the 6th of January, and all of the gulls were either sitting on the water about the ship, or riding the obstructional-current up-drafts off the mainsail. On the 7th, the wind changed to a cold northwester, starting convection currents which all of the gulls immediately began to use in soaring flight. On the 8th, the cold air continued over us, and the soaring was magnificent to see. The wind had risen to 28 miles per hour, which seemed only to increase the rate of convection and the ease of soaring. Late on the 9th of January, another warm front passed, and during the whole of the 10th and 11th the gulls were 'grounded,' or beating their way laboriously about on flapping wings. . . . .
> From a steep air slope over a windward embankment on Juniper Point (Woods Hole), the gulls can get enough altitude in a sixteen-miles-per-hour southwest wind, to enable them to glide directly to windward four-tenths of a mile to a roosting-place off the north-eastern tip of Nonamesset Island. It is amusing to note that, upon failing to reach the roosting place on the first trial, the birds will return to the region of the up-flow (while they still have enough altitude for the quick down-wind glide), rather than flap their wings for the last few hundred feet of the flight. Apparently several minutes of extra soaring time are preferable to a few seconds of wing-flapping.

Woodcock also observes (p. 222) that:

> At sea, gulls riding the up-drafts off 'Atlantis' sails are often seen to change over to convection-current soaring, but not without obvious searching for the convection eddies on flapping wings. When a convection up-flow is found, the birds must lift themselves fifty, a hundred, two hundred feet, depending upon the strength of the up-flow and of the wind, before the rising rate of the

air exceeds their own settling rate, and they are able to begin soaring. However, they detect the presence of the convection when they are flying just a few feet over the sea surface, for one sees them change abruptly from a wing-flapping horizontal flight to a steep climb, before they start the flying tactics characteristic of convection soaring.

It may be inquired whether the gulls studied by Woodcock were using some means of soaring other than rising air patterns. However, the only other known possibility would be dynamic soaring, namely, the shifting from one horizontal air current to another with different horizontal velocity. His analysis of the soaring patterns seems to dispose effectively of this possibility.

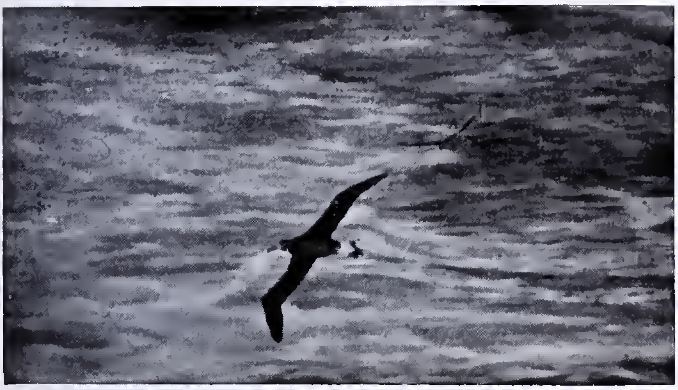
OCEAN GLIDERS AND LAND GLIDERS

There is an interesting difference between the gliding birds of the ocean and those of the land. The albatross and the condor are good examples, for both are highly specialized gliders. Living in environments with dependable currents of rising air, both have become almost entirely dependent on gliding for all their travels. In the process, however, the sea bird and land bird have developed completely different types of wings.

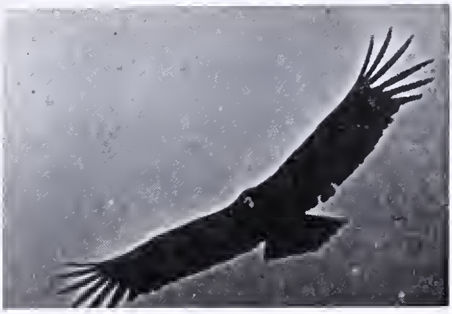
Like most gliding birds of the ocean, the albatross has long, narrow, pointed wings, the type generally considered most efficient for gliding (Fig. 138). Its aspect ratio is about 11 to 1. Some of the best man-made gliders have an even higher aspect ratio. However, such a wing is not good for active flight, for it puts too much strain on the flight muscles. Nature must compromise and keep the bird's wings short enough to allow the bird to take off and fly when necessary. So, through adaptation, the albatross has developed the wing best suited to its way of life.

Why should the condor, a land bird, have developed an entirely different wing, with an aspect ratio of about 8 to 1 and wide, deeply slotted tips? Most of the gliding or soaring birds of the land have this type of wing. Some water birds that soar over the land, such as the White Pelican, have them too. Birds with slotted wing tips can adjust the size of the slots. Some, perhaps all, can close them entirely.

Authorities on aerodynamics hold different opinions concerning the reasons for these slotted tips, which are generally considered



138. Black-footed Albatross.



139. California Condor.
Photograph courtesy
J. R. Pemberton.

The wings of ocean gliders and land gliders are completely different.

Most aerodynamic engineers consider the long, narrow wing of the albatross more efficient for both gliding and soaring than the broad, slotted wing of the condor. But soaring birds of the land have slotted wings.

less efficient than the narrow, pointed tips for both gliding and soaring. Slots give the wing more lift when it is near the stalling point, but at this point there is also more drag. So the total effect of the slot does not seem to increase gliding efficiency.

One explanation for the use of slots is that land birds must depend on air currents that are local and undependable. Instead of gliding at low altitudes, like the albatross, they must usually soar in a rising current of air until they are high enough to coast, perhaps several miles, to the next rising current. If the rising air column is very narrow, the bird will need not straight gliding efficiency but the ability to glide slowly, so that its momentum may not swing it outside the drifting air as it spirals upward. In the treacherous mountain air currents the slotted tips give better control of speed and stability.

However, the condor (Fig. 139) living in the mountains of the California coast range, among a sea of peaks, with a steady wind blowing in from the Pacific, has a dependable supply of air currents rising above the mountain slopes. Usually it need not go very high to start its glides. It almost never flaps its wings, except in taking off and landing, but will sail for miles on a straight level course at a fairly good speed, with its slots wide open. It can control the shape of the wing tip and the size of the slots. These slots make up about 40 per cent of the entire wing span, or 4 feet of a 10-foot span. It seems to be the steadiest, ablest glider among the hawks and vultures of its mountain home. Why, then, does it persist in using its wings in a way that most aerodynamic engineers consider inefficient?

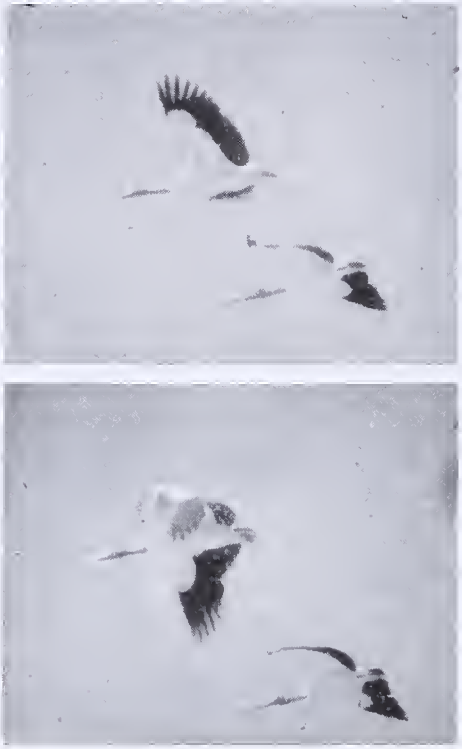
In making a study of the condor, either in the field or in photographs, one important point should be borne in mind, namely, that the primary feathers, besides being spread horizontally, are banked one over another, the highest in front, the lowest behind. When seen from the proper angle, below and behind, or above and in front, the feathers mask one another and appear closed. Seen from the opposite angles, however, they always appear open. Sitting on a mountain side, one can watch a condor at close range through powerful field glasses as it swings through a circle and see the tips, at a certain angle, appear to be completely closed, only to appear open again as the circle continues. Seen at the same point of the circle and from the same angle, the appearance is nearly always the same. The wing tip, one concludes, is a very deceptive thing to study.

As one searches for an answer to this riddle of the land and ocean gliders, one finds the argument for better stability with slotted wing tips less than convincing when one watches an albatross, with its pointed tips, circling and weaving its way among the obstruction currents over the ocean swells. The bird's movements remind one of a ballet dancer when compared with the smooth, straight glide of the condor. But the condor too can stop almost dead in its tracks and pivot on a pinpoint when it suddenly loses its rising air current. Perhaps the changeable mountain currents demand this instant response from the glider.

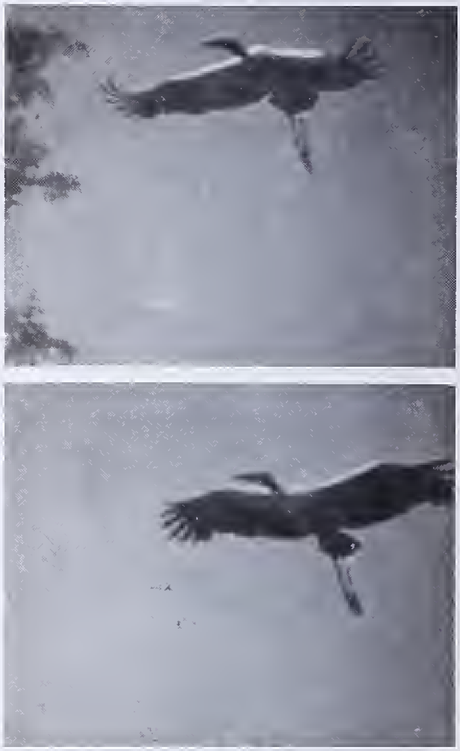
Another explanation may lie in the opportunities for dynamic soaring used by some of the hawks. There is a place in the California mountains where several families of Red-tailed Hawks nest in the face of a high cliff at an elevation of about 5000 feet. Not far away a mountain valley lies open to the prevailing west wind. A strong current of air rises up from this valley. The Red-tails hunt over the valley floors far below their home cliffs but seldom make the effort to fly the long climb back to their nests. Instead, they sail down-wind toward the rising air current, working up great speed, then swing sharply into the rising air, facing upwind with wings motionless and set at a very high angle of attack, apparently near the stalling angle, with slots wide open. The drive of their momentum will carry them against the drag of the high wing angle to build up tremendous lifting power. They shoot upward almost as if riding a giant elevator. Two such spirals will carry them upward 2000 feet or more, and they can then coast across to their nests.

In the swirling, eddying currents over the mountains, the condor, with its great size and weight, might find many spots where its momentum would drive it through a puff of head wind that would give it a lift similar to that of the Red-tails if its slotted wings were ready to take instant advantage of the chance. I have never seen condors use the technique of the Red-tails, though they often sailed past the same place.

Some glider designers believe that slotted tips give better efficiency to a glider that is soaring and trying for the greatest lift regardless of speed. I know of no published report of adequate tests of this type of wing. The condor wing tip is much more delicate and complicated to use than the simple pointed tip. Every feather must be shaped and set so that the air streaming over it will not interfere with the air stream of its neighbor. This adjustment must change in the shifting air currents. It is possible that the bird's sensitive adjustment permits greater efficiency than can be produced in a man-made machine. Again, the condor's wing, though more efficient for some kinds of gliding, may well be too delicate and complicated to use over the ocean, for wet feathers would be a great handicap to the wings' efficiency.



140 – 141

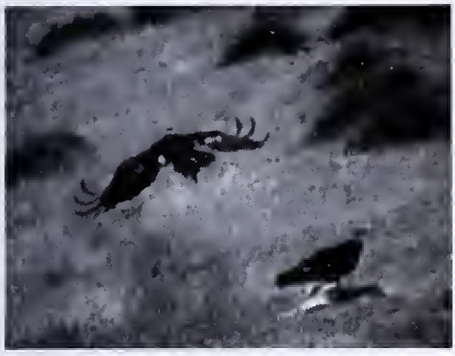


142 – 143

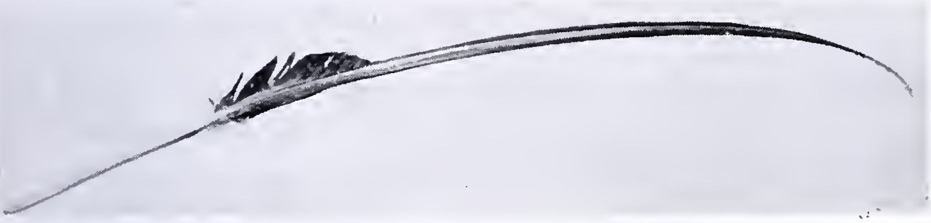
The Wood Ibis, master of gliding and soaring, uses both types of wing tip.

It habitually flies with a series of flaps, followed by a glide. It usually glides with tips pointed and soars with tips slotted. In Figures 140 and 141 the upper bird is flapping; the lower one is gliding on momentum gained from flapping. Its tips, acting as ailerons, change their angle, as the bird glides horizontally, from the first picture to the second.

The bird in Figures 142 and 143 is rising to clear some tree-tops. In the first picture it is beating its wings; in the second, 1.5 seconds later, it is gliding upward on the momentum gained from flapping—a technique comparable with dynamic soaring. Compare its wing tips with those of the gliding bird in Figures 140 and 141.

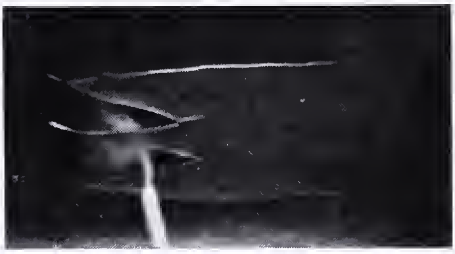


144. The primary feathers of this California Condor taking off are curved upward by tip vortex.



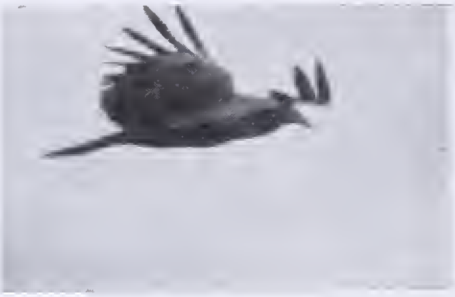
145. Primary feather of a California Condor.

146. Jet of smoke flowing past dummy wing tip simulating slotted wing tips of soaring bird, showing reduced tip vortex. Compare to Figure 7.

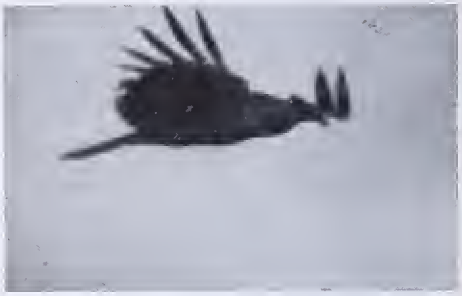


Some interesting questions are raised when we examine a wing built for soaring. The effect of the tip vortex on the primary feathers is demonstrated in the take-off of a condor (Fig. 144). Figure 145 shows one of these primaries at rest. To bend this feather from its normal downcurve to the position shown in Figure 144 requires six to eight ounces of upward pressure. (See Figure 7 for a tip vortex outlined in smoke.)

In these soaring birds the function of the slotted wing tip is not limited to speeding up the air flow. For if we compare photographs of the wing tips during active flight and in gliding, the



147. Downward wing beat of a Turkey Vulture, its primary feathers twisted into propellers.



148. Gliding Turkey Vulture. Owing to upward pressure from the tip vortex, the feathers are in almost the same position as that shown in Figure 147.

similarity of feather positions and twists strongly suggests that in each case the primary feathers are furnishing some forward drive.

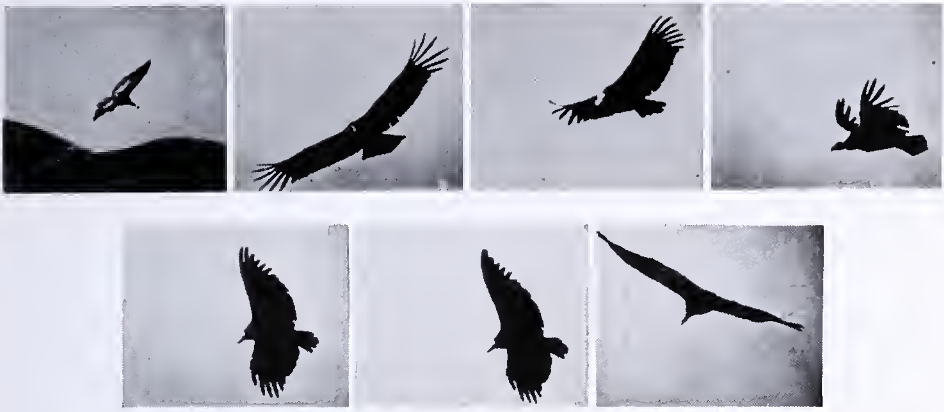
For example, Figure 147 shows a Turkey Vulture making a downward wing beat. The primary feathers are twisted into typical position to act as propellers. Figure 148 shows the same bird gliding with motionless wings just before starting the down stroke. The positions and angles of the feathers in the two pictures appear nearly alike.

In the first picture, the twisting of the feathers is caused by downward motion of the feather against the air. In the second, it is caused by upward motion of the air against the feather. In each case, the pressure of the air against the feather surface is in a direction that must furnish some forward drive.

In the case of the gliding bird, the upward momentum of the air in the tip vortex is furnishing some of the forward drive, which the bird would otherwise have had to acquire by coasting downward. Vortex is used in formation gliding (Fig. 156).

If this is so, the bird is actually recapturing some of the energy that would otherwise have been wasted in the tip vortex. The slotted wing, with its accurate feather adjustments, might well be more efficient for this purpose than the pointed wing.

When the wing tips are deeply slotted, as in the condor and the vulture, the primary feathers might be compared to a series of separate airfoils, or wings, of high aspect ratio. In the condor each pri-

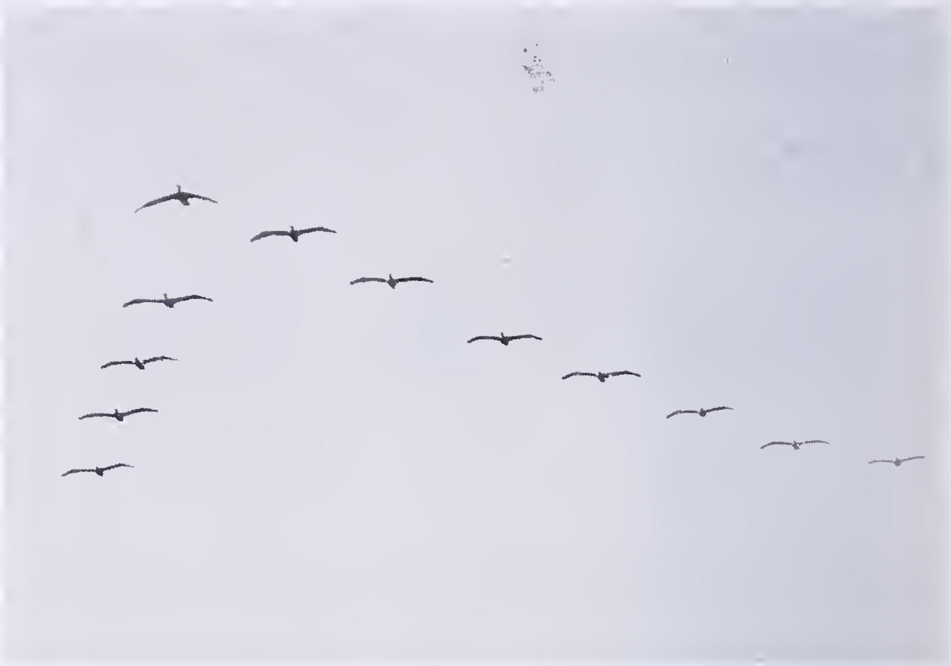


149 – 155. The deceptive appearance of the wing tips is demonstrated by this California Condor gliding through a circle with motionless wings. (See text.)

From motion pictures by J. R. Pemberton.

mary feather is set at an angle slightly different from the rest. Each one is adjusted to function in the air stream flowing from the one ahead of it. The front feather is the highest and most twisted, the next one somewhat less twisted and less bent, and so on.

The deceptive appearance of the tips is seen in Figures 149–155, where a condor glides through a circle on motionless wings. The tips change somewhat, but are not entirely closed in any of these pictures. We must visualize in three dimensions what the pictures can show only in two. In the first picture (Fig. 149), note the lump at the front edge of the bird's right wing. It is the wrist. If the line of its outer edge is followed, it can be seen as a dark shadow across the upper surface of the wing. This is the line of the hand and outer primary feather. What appears to be the pointed tip of the wing is really the rear corner of the open tip, with the forward primaries banked above it. The opposite tip is banked in the same way. The lengths of the first and second primaries may be compared in the next four pictures (Figs. 150—153) and in the sixth (Fig. 154) where the foreshortened appearance of the front primary shows it to be at a different angle from the others. Note the same feather in the last picture (Fig. 155), where it stands up above the other primaries, like a thin line. Follow this line down past the other primaries to the wrist, and we come to the same lump as in the first picture.



156. Brown Pelicans gliding "in formation." Each bird rests its inner wing tip on the rising side of the vortex caused by the bird ahead.

Courtesy, Hugo Schroder.

FORMATION FLYING

As a bird moves forward through the air, the vortex set up by the wing tip keeps on whirling for some time after the bird passes, just as the eddies in the wake of a boat are left whirling behind it. When birds glide or fly in formation they take advantage of these whirling wakes. The inner wing of each bird in a V formation gains support from the upward rising side of the whirl left by the outer wing of the bird ahead. Thus the energy wasted by each bird in making the vortex is passed on and used by the bird behind it. When planes fly in the same type of formation, the leading plane must burn more gas to supply the energy that the others pick up and use.

The Brown Pelicans shown gliding in formation in Figure 156 are using energy supplied in this way. Each bird rests its inner wing tip on the rising side of the vortex from the bird ahead.

FLIGHT SPEED

How fast does a bird fly? It is a question often asked. The answer must be: that depends on many factors. Is the bird cruising along enjoying the summer sun, or is it on some errand? Is it on a long journey, or is it hurrying out to look for its morning meal? Is it actively chasing that meal, or is it itself, perhaps, a prospective meal trying to elude its fate?

Under each of these varied conditions the bird will probably put a different proportion of its total energy into flight speed, and these proportions of energy will be translated into speed quite dissimilarly in different birds.

A pigeon, built for active flight, has a deep breastbone that gives its powerful muscles a good leverage on the wing. When pressed, the pigeon can put forth a tremendous burst of speed. A bird like the Herring Gull, built for gliding, with a long wing, small flight muscles, and comparatively shallow breastbone, has much less power in reserve for increased speed, and extra effort will bring it small returns in speed.

Moreover, birds experience definite seasonal cycles in condition of body and plumage which greatly affect their powers of flight. Some waterfowl lose the ability to fly when molting.

McCabe (1942) gives an interesting example of this changing ability. He reports timing the air speeds of Red-backed and other sandpipers, flushed on their feeding grounds and then pressed by a plane, mostly at altitudes below 300 feet. The maximum speeds varied from 45 to 55 miles per hour. On one occasion, however, when McCabe was flying at an altitude of 1500 feet at 90 miles per hour, two flocks of Red-backed and other smaller sandpipers overtook and passed him at a slight angle, going, he estimated, over 110 miles per hour. He raises the question whether these birds, apparently on migration, experienced changes of plumage or in metabolism that would permit faster flight.

In any measurement of flight speed it must be taken into consideration that air movement may have an effect on the bird entirely out of proportion to the velocity of the air current. A good glider with motionless wings may make 35 miles an hour on a current of air that is rising vertically at less than two miles an hour. With a wind blowing, any irregularity in the earth's surface, a clump of trees or a hillside, may produce a rising obstruction-current that will give the bird a boost enabling it to fly faster against the wind than it could have flown in still air.

A thermal, or rising current of warm air, though it may induce almost no perceptible air movement at the earth's surface, can give the same kind of boost to a bird flying through it. If the bird does a very little downhill coasting in still air it gets a similar effect.

It might appear, then, that a bird can build tremendous speed by coasting. However, with any increase in velocity, drag increases roughly as the square of the velocity increases. Twice the velocity gives about four times the drag, which sets an effective limit on a bird's top speed.

Wing efficiency is another factor in flight speed. We have seen that the lifting ability of a wing depends both on its size and on its speed through the air. In a bird's design there is the alternative of a big, slow-moving wing or a small, fast-moving one. The smaller the wing in proportion to the bird's weight, the faster it must move through the air.

It is possible to calculate the size and speed that an airplane wing must have to carry the weight of the plane. Engineers have tried, on the same basis, to calculate the speeds that different birds must have. But with a bird, accurate calculation has proved impossible, for in active flight the angles and velocities of different parts of the wing are constantly changing, and part of the lift is supplied by direct downward beating against the air.

Some interesting studies of wing area and body weight have been made by Poole (1938), who has shown considerable correlation between wing loading and flight characteristics. His measurements do not include the tail area, which may vary considerably in the same bird under different flight conditions. Since the angle, velocity, and method of functioning of each part change during succeeding phases of the wing beat, the most exact measurements can give only a rough approximation of the actual loading on the various parts of the wing.

In general, the loading for any one species is fairly uniform, but there may be a considerable variation within a species, depending upon the sex and condition of the bird. A bird in good, fat condition will obviously have a higher wing loading than one of the same frame and wing size but in poorer condition. Poole (1935, p. 513) has found, in a limited series of measurements, that where sexes differ in weight, the heavier sex has a lower aspect ratio. Poole also indicates that in closely related species there may be a considerable difference in wing loading. The Eastern Crow, for example, has a wing area of 2.43 sq. cm. per gram, compared with 3.325 sq. cm. per gram for the smaller Fish Crow.

In general, this ratio holds true for all birds examined. The smaller the bird, the higher the wing ratio in comparison with that of similar but larger birds. This relation may be accounted for by the slower flight of some of the smaller birds or, in the fast-flying swifts and swallows, by a slow wingbeat. The hummingbird, with its very fast wingbeat, has lower ratio than other birds near its size.

The least efficient areas of the wing are along the rear, or trailing, edge and the tip, where the air flow is disturbed by eddies. The smaller the wing, the bigger the proportion of the wing that must be near these inefficient edges. A smaller wing will therefore tend to be less efficient than a bigger one of the same design. This fact, Poole (1938) suggests, explains the proportionately larger wing area of the smaller birds.

The wing area of different birds of the same weight varies greatly, depending upon their way of life. In some birds, for example, that inhabit thick underbrush or water, toughness and versatility are more important in a wing than greater flying efficiency. So we may think of the bird community as organized, through competition and evolution, in such a way that each species is adapted to fill some particular niche in nature, where it can excel all others, and so live with the least interference from other species. Thus a body is developed with the best all-round equipment for its way of life.

The American Egret and the American Pintail both work for their living in shallow water, and are of about the same weight. But they use different food and need different equipment to catch it and different wings to carry the special equipment. The duck has few landing problems, since its chief need in flight is to cover ground fast, with small wings that will be manageable in the water. The egret, in contrast, must have long legs to wade in the marshes where it stalks its prey. It must be able to land slowly and carefully, to preserve these long legs. A pintail weighing 970 grams had a wing area of 761 sq. cm., a ratio of .784, while an egret weighing 899 grams had a wing area of 2528 sq. cm., a ratio of 2.33, or three times as much.

Again, the Great Blue Heron and the Common Loon both seek food in water, but the loon is built to hunt in deeper water. Weighing 2425 grams as compared to 1905, for the heron, the loon has a wing area of 1358 sq. cm., with a ratio of .56, as compared to the heron's 4436 sq. cm., with a ratio of 2.33. The heron must fly slowly; the loon cannot and need not.

Thus, with their different requirements and equipment, all these different birds can live in the same community without serious competition.

Some idea of the wing loading of various groups of birds, according to their size and living habits, is given by the following measurements from the list by Poole (1938).

TABLE 1

WING LOADING OF BIRDS OF DIFFERENT SIZES AND LIVING HABITS

In some instances Poole's measurements are individual, in others, averages.

Species		*Weight (grams)*	*Wing area (sq. cm.)*	*Wing area per gram*
Ruby-throated Hummingbird ♂	1	2.98	12.40	4.16
Eastern Golden-crowned Kinglet	1	5.75	51.00	8.87
Magnolia Warbler	1	9.20	69.00	7.50
Eastern Winter Wren	1	9.40	41.00	4.36
Barn Swallow	2	17.00	118.50	6.96
Swamp Sparrow	3	17.00	73.00	4.30
Leach's Petrel	1	26.50	251.00	9.47
Rose-breasted Grosbeak ♂	1	40.00	166.50	4.16
Eastern Fox Sparrow	1	40.50	116.00	2.85
Eastern Nighthawk	2	75.25	349.50	4.64
Eastern Robin	1	82.00	244.00	2.97
Northern Barred Owl	1	510.00	1830.00	3.59
Eastern Ruffed Grouse	1	516.50	527.00	1.02
Eastern Crow	2	552.50	1344.00	2.43
Lesser Scaup Duck ♀	1	763.00	472.00	0.62
Herring Gull	1	850.00	2006.00	2.40
Ring-necked Pheasant	3	1304.00	917.00	0.701
Snowy Owl ♂	1	1404.00	2576.00	1.835

An analysis of these data shows some interesting comparisons. The tree-dwelling kinglet and the warbler resemble each other in wing ratio but differ from the bush-dwelling wren. The larger Fox Sparrow compares with the tree-dwelling grosbeak. The Nighthawk, living on the wing, may be compared with the Robin, an active bird, but one having less need for continuous flight and so able to put more of its energy into a faster wingbeat, with a smaller wing. The Barred Owl must be able to fly slowly and to maneuver in the woods. It needs a bigger wing than the grouse, which depends on speed and a fast wingbeat. The Herring Gull, a glider depending on air currents and needing slow speed in searching for its food from above, has nearly four times the wing area of the scaup duck, whose chief requirement is speed.

The hummingbird and Leach's Petrel are in a class apart. Both must hover nearly motionless at times in feeding. Both, to get sufficient lift, must compensate for the lack of forward speed. The hummingbird accomplishes it by a fast wingbeat, with a wing small enough to maneuver among the flowers. The petrel must make longer flights and must use its energy more efficiently. It has big wings that can be used almost like parachutes and allow a slow wingbeat. But in the hummingbird's feeding grounds the petrel would be helpless with such wings.

At the Hawk Mountain Sanctuary in Pennsylvania, Broun and Goodwin (1943) made careful measurements of speed of hawks and crows on migration. These are, chiefly, not true flight speeds but the gliding speeds of birds sailing on rising air currents. These data show considerable variation in speed which appears to bear little relation to wind velocity. However, the average speeds of the different species are fairly similar, as the following summary shows.

Poole (1938) states that he has often observed hawks flexing or extending their wings in sailing past Hawk Mountain. In a strong air current they flex their wings to reduce drag and allow greater speed; in a slow current they extend their wings to the full to get maximum lift.

The ability of the Osprey to glide at 80 miles an hour in a wind of only 4 miles an hour demonstrates the help a bird may get from rising air currents. It shows too the difficulty of measuring accurately a bird's ability to make speed under its own power.

The speed of birds has often been measured without an accompanying measure of the help they may be getting from the air. A list of some of these measurements may be of interest, but it should be noted that the data indicate traveling speed rather than flying ability.

Table 2

Speed and Wing Loading of Various Species of Birds*

Species	*Total speed records*	*Speed range (m.p.h.)*	*Average speed (m.p.h.)*	*Weight (grams)*	*Wing area (sq. cm.)*	*Wing area per gram*
Turkey Vulture	1	34	------	2409.0	4356	1.81
Eastern Goshawk	1	38	------	♂ 848.6	1480	1.74
Sharp-shinned Hawk	37	16–60	30.0	♂ 97.5	439	4.50
Cooper's Hawk	12	21–55	29.3	428.5	898	2.07
Eastern Red-tailed Hawk	54	20–40	29.0	♂ 875.0	1878	2.14
Northern Red-shouldered Hawk	7	18–34	28.3	804.0	1656	2.11
Broad-winged Hawk	8	20–40	31.7	376.0	1012	2.69
American Golden Eagle	2	28–32	30.0	♀ 4664.0	6520	1.397
Bald Eagle	2	36–44	40.0	----------	--------	--------
Marsh Hawk	4	21–38	28.7	♀ 615.0	1696	2.75
Osprey	16	20–80†	41.5	1797.5	3211	1.79
Duck Hawk	3	28–32	30.0	♂ 712.0	1146	1.61
” ”				♀ 1222.5	1342	1.10
Eastern Pigeon Hawk	1	28	------	♂ 173.0	410	2.37
Eastern Sparrow Hawk	4	22–36	26.2	♀ 137.0	372	2.74
Eastern Crow	15	17–35	26.0	552.5	1344	2.43

*Speed records from Broun and Goodwin (1943); weights and measurements from Poole (1938).

†One bird made a speed of 80 m.p.h. with a wind of 4 m.p.h., sailing with only two half-flaps over a course of two-thirds of a mile, evidently in a strong thermal updraft.

TABLE 3
SPEED OF BIRDS UNDER VARIOUS CONDITIONS

Species	*Speed range (m.p.h.)*	*Conditions*	**Source*
Great Blue Heron	18–29	Cruising	C
” ” ”	36	Pressed	C
American Egret	17		
” ”	32	Ahead of car	S
Black-crowned Night Heron	18–35	Cruising; pressed	C
Snowy Egret	30	Pressed	C
Sandhill Crane	35	No wind	C
Whistling Swan	25		C
” ”	50-55	Pressed by plane	
Canada Goose	20	Easy flight	C
” ”	45–60	Pressed by plane	
Snow Goose	50	Pressed by plane	
Mallard	55–60	Pressed by plane	
Cinnamon Teal	32	Easy flight	
” ”	59	Chased	
Shoveller Duck	47–53	Easy flight	
Redhead	31	Cruising	C
”	50–55	Pressed	C
Ferruginous Rough-leg	30–35		C
American Golden Eagle	120	Chased by peregrines—stop watch	
Duck Hawk	175–180	Pressed by plane	
Sharp-tailed Grouse	22–33		C
Bob-white	28–49	Many tests	
Pheasant	60	Average top speed	
Sandhill Crane	35	No wind	C
Woodcock	5–13		
Long-billed Curlew	35–45	Cruising	C
” ” ”	50	Ahead of car	C
Spotted Sandpiper	21–30	Cruising	C
Western Willet	35–47		C
Mourning Dove	26–41		
Short-eared Owl	15–26	No wind	C
Great Horned Owl	40	Slight rear wind	C
Burrowing Owl	12	Cruising	C
Ruby-throated Hummingbird	45–55	Easy flight	
Red-shafted Flicker	28	Cruising; no wind	C
Kingbird	11–23		
Horned Lark	23–54		
Barn Swallow	20–46		
Cliff Swallow	29	Cruising	C
Crow	25-60		
Catbird	12–16		
Robin	17–36		
Shrike	28–45		
Yellow Warbler	22	Easy flight	C
Yellow-headed Blackbird	20-35	Cruising	C
Red-winged Blackbird	22–28		

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*Letters under "Source" refer to speeds recorded by following authors: C—Cottam, Williams, and Sooter (1942); B—Broun and Goodwin (1943); S—J. H. Storer. All others from Cooke (1937).

MANEUVERABILITY

One of the most interesting aspects of bird flight, and one of the most difficult to describe or illustrate by photography, is the ability of birds to maneuver—to perform actions outside the ordinary routine of flying. Such actions are likely to take only seconds of time, and the photographer who can focus his camera on one of them is fortunate.

Some flight maneuvers are merely playful. Others are skillful and thrilling shortcuts, such as the dive of a soaring Wood Ibis, or the meeting of a sudden emergency, such as the avoidance of a collision with another bird, or striking an air pocket. Most exciting of all are the maneuvers in the deadly serious business of attack and escape.

Many bird watchers have thrilled at the sight of an Osprey doing loops or backward somersaults in the air. On a bright afternoon, perhaps after a good catch has met the Osprey family's food requirements for the day, one may sometimes hear the shrill call of the bird overhead. It seems to be hovering, but is looking upward, not down toward the water as it does when hunting. It flies forward with rather labored flight, evidently trying to gain altitude as well as momentum. Then, with a sudden burst of speed it zooms upward, with wings still flapping, until it is headed vertically upward and starts to fall over backward. However, I have never seen it actually go over. The embryo loop turns into a sideslip, which levels off into straight flight again.

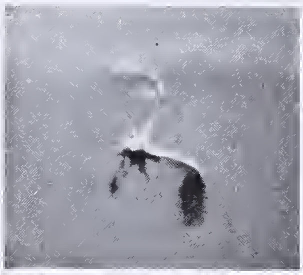
The Bald Eagle may carry this loop a little farther. Near Jacksonville, Florida, Mr. S. A. Grimes showed me a nest where the old birds seemed anxious to impress all intruders with their prowess. When we approached, the old birds flew up, although not very far, and started somersaulting in the air. These birds actually turned over on their backs and beat their wings once or twice in that position. From the motion pictures, which are too small to show much detail, it appears that the birds lost little altitude in the process and made little forward progress. The propellers were apparently held nearly horizontal on the back stroke, which in this instance would be the downward stroke, as if lift were gained from a downward push.

A flock of several hundred White Ibises, stretched out in a long, undulating line against a vivid blue sky, is one of the most beautiful bird exhibits to be seen in Florida. Sometimes one or two or three birds together will drop from this line and fall head over heels, looking much like falling leaves as they whirl over and over. After a considerable fall they regain their balance and fly back into line. Although the birds appear to be completely out of control as they fall, their action is probably nothing but play.

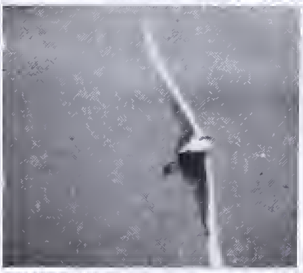
Sometimes, when returning to their rookery, these White Ibis fly very high, perhaps to make use of some favoring air current, until directly over the rookery. Then, they dive straight downward with roaring wings outstretched horizontally in a 90-degree stall, feathers ruffling all along the back. The head and legs hang downward as though to help keep balance. A little above the treetops the wings rotate to an angle to give forward motion and lift, and the bird sails in to a perfect landing.

At noontime the Wood Ibis often spend an hour or two soaring high above the rookery. As the birds bank steeply in going around their great circles, the sun flashes off their white backs, and to the observer below they stand out as dots of sparkling white against the deep blue sky. Continuing around the circle, their flashing backs turn away, and with their shaded undersides reflecting less light they become invisible until they reach the reflection point again. As one watches, it is hard to realize at what a sharp angle they must be banking to reflect the sun's rays from their white backs into one's eyes. Suddenly a dark pin point overhead grows into a black spot. A Wood Ibis is diving head first, its wings behind and close together, looking almost like a huge closed umbrella, whirling slowly as it falls. Slowly the wing tips spread apart, and, roaring through the air like a falling plane, the bird slowly levels off and coasts in to the rookery. That feathers can stand the strain of such pressure from the air is a marvel.

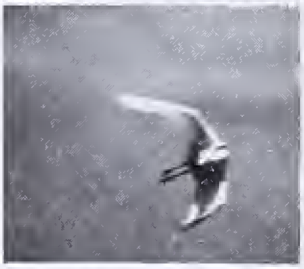
The Swallow-tailed Kite, a much lighter bird, may make a different kind of dive. I have seen these birds soaring so high as to be almost out of sight, when apparently attracted by the glint of a dragonfly's wing, one would dive head first, wings nearly closed, the wrists slightly forward and the tips slightly away from the body. Such a drop appears to be a gravity dive, no doubt with guidance



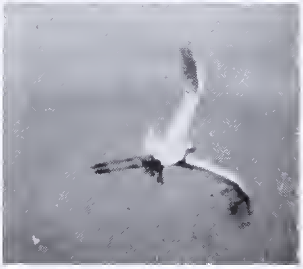
157. The egret sees the photographer ahead and starts to roll. On this up stroke, its legs still dangling, it raises its right wing high, largely supported, meanwhile, by the left wing.



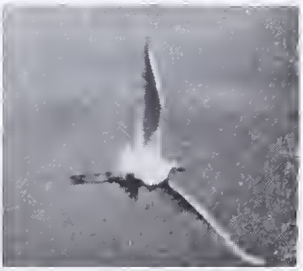
158. 12 frames later. End of the down stroke; propellers still thrusting – note the downward curve of their leading edges.



159. 15 frames later. The pressure of its right wing has rolled the bird onto its side; both propellers are thrusting hard; the head is still upright.



160. 14 frames later. End of the up stroke; the wings stretched far forward to pull the body around, the tail spread wide, its feathers separated; the legs kick forward evidently compensating the wing action and not merely the pull of gravity as might appear from action in normal flight.



161. 5 frames later. The egret's left wing gives the final lift to level the body, which will be level in eight more frames. The legs are kicking upward again, and both propellers are thrusting, still pulling the body around.

An American Egret banking for a sharp turn.

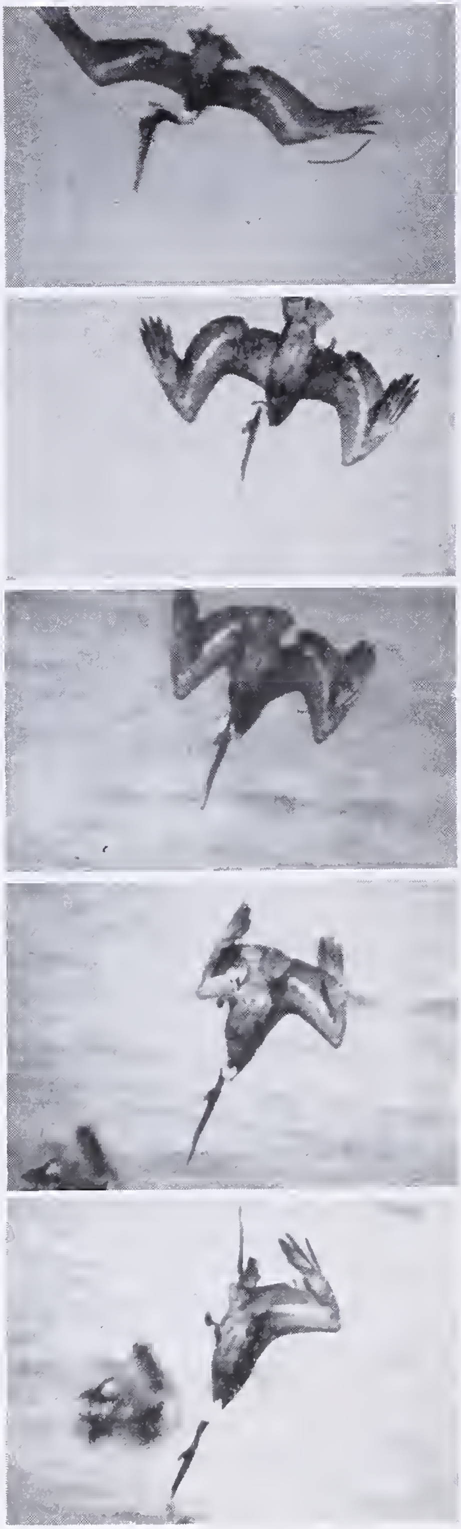
This wing action contrasts with a normal flying stroke in that the wings move forward on the up stroke (Fig. 160) in order to pull the body around. Normally they would move backwards on the up stroke.

by wings and tail, but with no forward drive by the wings and no checking. Just above the treetops, so close that a smash-up seems inevitable, the kite spreads its wings, checking its motion with a suddenness that wrenches the wings upward in a whirl of ruffled feathers. Its bill closes with a loud snap on the unlucky dragonfly, and some quick flaps of the wings restore equilibrium. It is a breath-taking and effective ending, though not very graceful, the only hurried or ungraceful act in which I have ever seen a Swallow-tailed Kite indulge.

Sometimes, if the dragonfly shifts position, the kite will change direction, and instead of ending in a head-first dive, it swoops down at an angle, then zooms up in a graceful curve, picking up the dragonfly en route. Sometimes, when flying near the ground, the bird will reach down with one foot and pick up a grasshopper without pausing in its course.

Diving into water for a fish requires skillful maneuvering and much finesse. When an Osprey sees a fish below, it drops one wing and "peels off" sidewise like a plane before going into a vertical dive. The wings are kept partly open to control speed and direction with the help of the tail. Then, at the last moment, the feet shoot down past the bird's head to strike the fish, claws first, in a fountain of spray. A perfect take-off follows. As the wings come to the surface they sweep backward on the first stroke, the outer halves turning over so that the upper sides face downward. Horizontal strokes of the wings, forward and back, lift the bird straight up like a helicopter. A few feet above the surface of the water the angle of the wingbeat shifts quickly into high with the regular flying stroke, and the bird hurries off with its fish. In this take-off, when the wing tips once leave the water they do not touch it again, but sweep parallel to its surface. For most land birds such a take-off, with soaking wet feathers, would probably be impossible. However, the deep notching of the Osprey's first primary feathers permits their separation so that, whether wet or dry, they can open the needed slots.

The Brown Pelican dives with a different technique (Fig. 162–170). Depending on its bill instead of its claws, it strikes the water head first. With an armored and streamlined nose, it can make deeper dives, controlling the speed and depth of the dive with its



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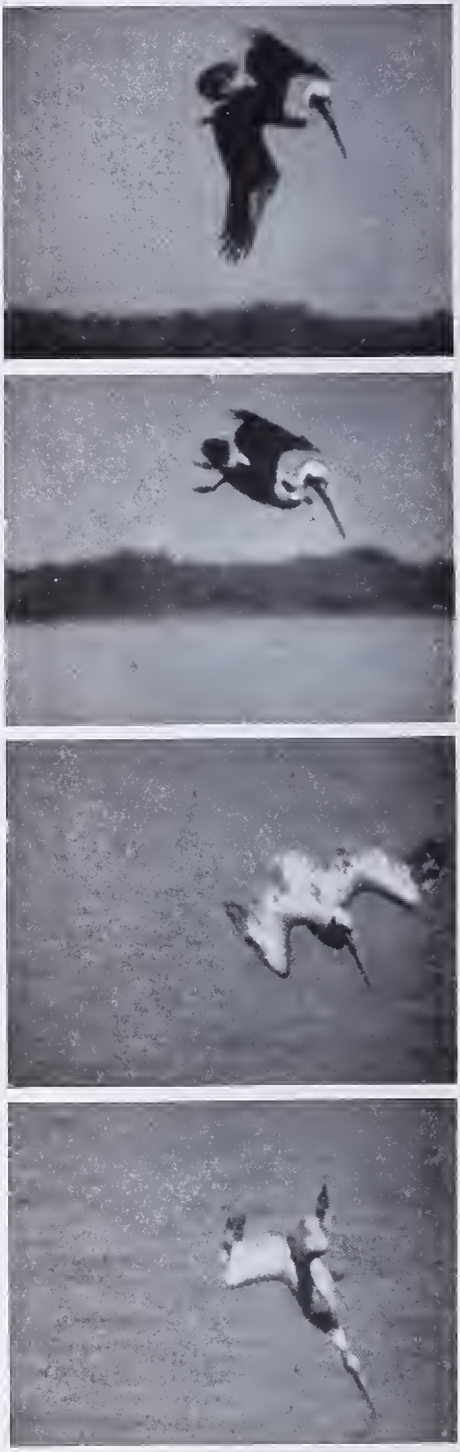


167 – 170

Diving techniques.

The Brown Pelican, when diving for a fish, controls its speed and the depth of its dive by the angle of its glide and the spread of its wings. The bird in Figures 162 – 166 is making a deep dive. It is seen from its under (belly) side. The bird in Figures 167 – 170 turns during its dive, apparently to follow the direction of the fish. Note the use of tail and wings in steering. In the last picture, the bird's left wing uses a double angle of elbow and wrist. The Pelican always turns as it strikes the water and catches a fish crosswise in its bill, probably to break the back of the fish.

wings. For a deep, fast dive the wings are not closed against the body, but trail out straight behind the tail, giving the effect of a closed umbrella. The bird always turns as it strikes the fish, apparently catching it crosswise in its bill and breaking its back in this way. My motion pictures of diving pelicans show most of the birds turning to the left, counterclockwise, as they strike. The impulse for a left turn would naturally come from the right wing. Are most pelicans right-handed?

With its light body and webbed feet, the pelican has little difficulty in leaving the water. Unlike the Osprey, it can take off in the conventional way by hopping along the surface to gather speed.

One of the most skillful bits of maneuvering I have seen was performed by a Turkey Vulture when attacked by a pair of Bald Eagles. As the vulture flew past the eagle's nest, perhaps a hundred yards away, one of the eagles flew toward it, though not very fast, as if not wanting to arouse suspicion. The vulture kept on its course, but the eagle, as it approached, suddenly put on speed and the vulture swerved sharply away, increasing its own speed at the same time. The eagle, much faster than the vulture, rose above it by perhaps 30 feet, and slightly to one side, then dove with a powerful sweep of the wings. The vulture kept straight ahead until the eagle seemed ready to strike. Then, with a lightning flip, the vulture dropped sidewise and for an instant seemed to be suspended from the tip of the wing nearest the eagle, which shot down harmlessly through the space just vacated by the vulture's body.

The second eagle of the pair had now joined the pursuit, and by this time was overhead and was diving before the vulture had regained equilibrium. But the vulture righted itself in time to repeat its sideslip successfully. The eagles now took turns making short, vicious dives, and it did not seem possible that the vulture could recover after one dodge in time for the next. But the eagles did not seem to consider the possibilty of deflection and were never in a position to strike the bird in its sideslip, although they must always have aimed ahead of the vulture to compensate for its forward flight. Meanwhile, it was putting on speed between dodges, stretching its neck in the most unvulture-like fashion, and flying with very fast wing beats toward a palm hammock, where it had a better chance to dodge, with less chance for teamwork by its attackers, and after a few fast circles through the hammock the eagles gave up the chase.

Off the cliffs of Bonaventure Island I witnessed another feat of dodging. Here a Barn Swallow, whose small wingspread made the vulture's method impracticable, was attacked by a pair of Duck Hawks. They swooped in nearly vertical power dives while the swallow, continuing on its course until the last possible instant, would suddenly dodge with wildly fluttering wings, letting the hawk shoot past and zoom up to be in position overhead again, almost before the swallow had regained a level flight. The hawks took turns diving, with one always in position to head the swallow away from the shelter of the cliffs. But after some hairbreadth escapes it managed to reach shelter and the hawks gave up the chase.

I have seen a Duck Hawk fly up to look over a trio of young Ospreys on the nest. The adult Osprey flew at it, and the Duck Hawk turned tail. Whether the hawk was using its top speed may be questioned, but the Osprey kept pace with fast wingbeats, both elbows and wrists appearing to be considerably more bent than in normal flight, perhaps to cut down the leverage and drag of the full wingspread at such high speed. The Duck Hawk kept within a few hundred feet of the ocean surface. The Osprey, from a position slightly above the hawk, lunged forward and downward, while the Duck Hawk shot sideways and upward, apparently with plenty of power in reserve for a wide sweep. But the Osprey persisted, and was able to follow and make several such attacks before pursuer and pursued were out of sight.

A Great Blue Heron once flew past me over a New Brunswick marsh, uttering nervous, high-pitched croaks quite unlike the usual heron cry. Then it started to circle upward, with alternate flapping and gliding, evidently feeling for the aid of a light current of rising air. Not far behind was an immature Bald Eagle, which, on reaching the area of rising air, also started circling upward. The heron, with a greater wing area in proportion to weight, proved the better at soaring and, after gaining a considerable advantage in altitude, set off across country. Then, being able to add to its flight speed by coasting, it soon outdistanced the eagle, which gave up the chase.

In straightaway flight the more powerful eagle could probably have overtaken the heron fairly easily. The eagle is an expert at soaring, while a soaring Great Blue Heron is a rare sight. However, with its better ratio of wing area to weight, the heron may be able to flap and glide upward faster than an eagle, even without the help of a rising air current.

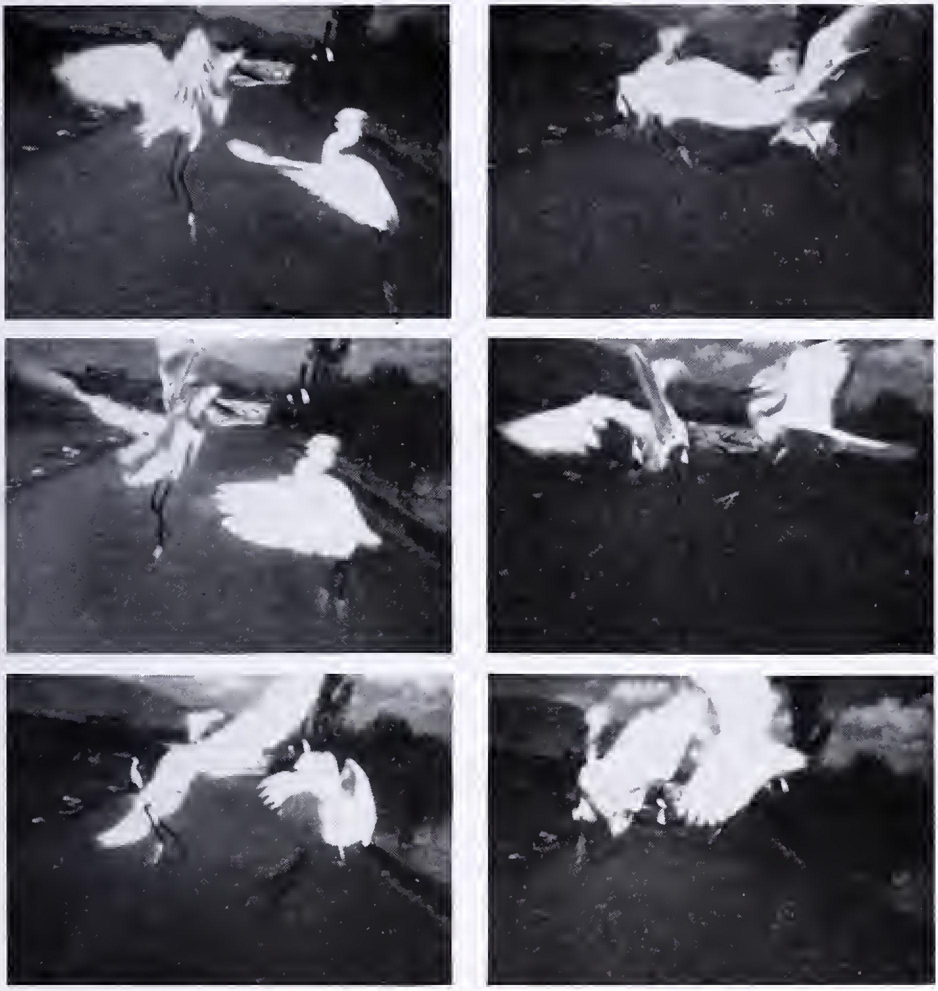
BACKWARD FLIGHT

Backward flight would appear to be in a class with stunt flying. I have slow-motion pictures of a pair of Snowy Egrets fighting in the air, in which one of the birds flies backward for several strokes without losing altitude (Figs. 171–176). The wing motion is nearly horizontal, forward and back, much like the helicopter motion shown in Figures 89 to 94. The chief difference in backward flight is that on the forward stroke the lower surface of the wing strikes the air a little more directly and at a steeper angle, to give backward pressure as well as lift. In this case the egret kept its body in an almost vertical position, apparently ready to shelter its head behind its forward-snapping wings, or to kick its opponent in the face if it came too near.

The hummingbird finds backward flight a useful accomplishment when it wants to withdraw its long bill from the honey store of a flower (Figs. 59, 60). In flying backward it uses the same principle as the egret, but it undoubtedly becomes a helicopter more easily, owing to the ability to rotate its wings more freely. Like most small birds, the hummingbird moves its wings too rapidly for the eye to follow, and its flight can be studied only through the eye of a camera.

* * *

Though the small bird's flight can be studied only by means of the camera, the flight of larger ones, beginning with those the size of a pigeon, can be followed with the eye. When the bird lover has developed a sense of what is happening in the air around the wing, especially in the moments of take-off, landing, and maneuvering, he will find that the observation of flight has become a fascinating addition to the field of bird study.



171 – 173 174 – 176

Backward flight.

A bird can fly backward. In a dispute over fishing rights, the Snowy Egret on the right attacks another, its wings snapping forward so hard that they cross in front; the bird on the left throws its wings back to get a grip on the air for backward flight (Figs. 171-172). In Figure 173, the left bird is backing away. The curve of its wings attest their pressure against the air. The bird on the right is drawing its wings back for another stroke. In Figure 174, the left bird finishes its stroke. Note that the plumes on its head have begun streaming to the right, showing that the bird is moving to the left. In Figure 175, the left bird throws back its left wing for another grip on the air. In Figure 176, the left bird finishes another stroke. Its plumes are now streaming straight out to the right. In the course of this flight, one of the birds flew backward for half a dozen strokes or more, rising part of the time, and apparently could have continued farther. (Figure 172, 8 frames later than 171; 173, 7 frames later; 174, 5 frames [illegible] frames later; 176, 12 frames later.)

Glossary

Aileron. See *flap.*

Aerodynemics. The branch of dynamics which treats of the air and other gaseous bodies under the action of force, and of their mechanical effects (Webster).

Alula. The "spurious wing" of a bird, corresponding to the thumb in man.

Angle of attack, tilt. The angle at which the chord of an airfoil (wing) meets the direction of the wind.

Aspect ratio. The ratio of a wing's length to its width.

Barb. One of the fibers that make up the vane of a feather.

Barbicel. A small process, or hook, on the barbules of a feather.

Barbule. One of the processes that fringe the barbs of a feather.

Covert feathers, coverts. The feathers covering the bases of the quills of the wings and tail of a bird.

Drag. Backward pressure; force of the air opposing wing movement.

Flap. A wing device to increase lift for a low-speed landing.

Induced drag. Drag caused by any change in pressure against the air.

Lift. Force opposed to gravity.

Obstruction current. An air current deflected upward by an obstruction.

Patagium. Elastic membrane extending along the forward edge of the wing from shoulder to wrist, and along the rear edge from outer bone tip to elbow.

Primary feathers, primaries. The principal outer feathers of the wing, which make up the propeller. They are attached to the bones of the hand.

Profile drag. Drag caused by simple movement of the wing through the air and due to friction.

Quill. The shaft, or barrel and rachis, of a feather.

Scapular feathers, scapulars. The feathers growing from the scapular membrane.

Secondary feathers, secondaries. The longer feathers on the middle section (forearm) of the wing, which provide most of the lifting surface.

Slot. A wing device to increase lift and prevent stalling at low speeds.

Stalling point or *angle.* Angle where loss of lift begins.

Tertiary feathers, tertiaries. The feathers growing from the elbow.

Thermal. A rising current of warm air.

Tilt. See *angle of attack.*

Tip vortex. Whirl of air at tip of wing.

Trailing edge. Rear edge of wing.

Vane. The flat expanded part of a feather bordering the quill.

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